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INFLUENCE OF NOISE CONTROL COMPONENTS AND STRUCTURES ON TURBOJET ENGINE TESTING AND AIRCRAFT GROUND OPERATION

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NOTICES

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FOREWORD

This report is the companion document to a series of three reports entitled "Noise Control for Aircraft Engine Test Cells and Ground Run-Up Suppressors", WADC TR 58-202, Volumes I, II, and III, (References 1, 2, and 3). The three previous volumes of this series were concerned with: (a) measurement and analysis of acoustical performance, (b) design and planning for noise control, and (c) an engineering analysis of measurement procedures and design data. This volume will discuss both the design and the operational dynamics of turbojet engine test cells and ground run-up facilities. This report has been prepared by the firm of Kittell-Lacy, Inc., under Contract No. AF 33(616)-5789 for the Biomedical Laboratory, 6570 Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. The work was done in support of Project No. 7231 "Biomechanics of Aerospace Operations", Task No. 723104, Biodynamic Environment Section, Bioacoustics Branch, Biomedical Laboratory. The background material and the research information used in the preparation of this report was obtained in 1958 and 1959 and therefore represent the state-of-the-art of noise suppression techniques and the test cell construction to that time.

Mr. Rollin O. Boe of Kittell-Lacy, Inc., deserves a great deal of credit for his invaluable contributions to the following work. Also much credit is due Mrs. Ann B. Saylor (formerly of Kittell-Lacy, Inc.) for her editorial comments and suggestions. Mr. Boe and Mrs. Saylor are primarily responsible for the authorship of Appendices A through D. Thanks are due Mr. D. L. Gossett and Mr. D. B. Hill (formerly of Kittell-Lacy, Inc.) for help in the discussions of cell instrumentation.

The author is indebted to Capt. W. C. Elrod, formerly of the Biomedical Laboratory, for suggestions and criticisms which have aided greatly in the preparation of this report and for providing technical supervision.

The final technical editing of this report was the responsibility of Mr. G. W. Barton of the Bioacoustics Branch, Biomedical Laboratory.

ABSTRACT

There has been a need for summarizing and establishing adequate aerodynamic and thermodynamic design criteria for turbojet engine test cells and ground run-up suppressors. These criteria are discussed and their uses are illustrated by examples of typical design problem solutions. The presence of noise suppression structures can have significant influences upon the operation of the turbojet engine. These influences are enumerated and evaluated with recommendations for establishing maximum acceptable effects. Typical test cell configurations are presented and design criteria are established for providing noise suppression facilities which may be utilized for testing a full size aircraft or an engine by itself. These facilities can be either permanent structures or portable units.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Jos M Quashnock
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SECTION I

INTRODUCTION

The objective of this report is to acquaint the test cell operating engineer and the procurement officer with the basic sound-attenuation system components and their relationship to the fundamental aerodynamic and thermodynamic aspects of test cell operation, evaluation and design.

Section II has been devoted to an explanation of cell sound-suppression components and the nomenclature of cell operational facilities. The fundamental types of noise control components are discussed with emphasis on each component's relationship to the overall cell design.

Section III of this volume should acquaint the reader with fundamental knowledge of engine operation. This Section discusses the functioning of engines operated both in test cells and in ground run-up facilities. The aerodynamic and thermodynamic parameters which should be investigated in typical test cells are defined. The necessary criteria are provided for a cell designed to insure acceptable engine performance. Then, some allowable restrictions, which test cells impose upon engine operations, are discussed as are the methods for extrapolating inordinate engine performance data to determine actual performance.

Aerodynamic and thermodynamic considerations which influence engine operation are discussed in detail in Section IV. This Section contains, primarily, recommendations for design planning.

The design engineer and procuring agency must consider the feasibility of constructing a test cell that will not only accommodate presently available engines, but will also be adaptable to future engines. Thus, these personnel must be aware of those factors which dictate acceptable cell design. Section V describes the criteria for acceptable cell design and discusses cell dynamics equations and component design limits.

When new cells are completed or when existing cells have unknown operating conditions, facility evaluation is a necessity. Section VI describes the instrumentation required to adequately measure test cell aerodynamic and thermodynamic performance. The influence of the test cell, or the ground run-up suppressor, on engine operation is defined, and that influence is presented as a calibration correction.

Several appendices are included to cover specific problems such as cell ram pressure corrections for thrust measurement, prediction of airflow performance within the test cell, and calculation of momentum pumping efficiency through the augmenter tube.

Section VII summarizes the main points of this volume and presents some specific cell design and evaluation recommendations.

SECTION II

FUNCTIONS OF MAJOR SUPPRESSION COMPONENTS

Major noise suppression components fall into three categories. Specifically, these are components that are associated with (1) the test section or engine room, (2) the intake system, and (3) the exhaust system.

Within the test section the major noise control components are the room geometry and the absorption material which is applied to the walls and ceiling.

The intake system usually consists of an intake stack with parallel panels or ducts lined with absorption materials. Bends of 90 or 180 degrees may be considered a part of the suppression method. Separate, secondary-air intake ducts may be included in this system when additional airflow is required.

The exhaust system is more complex than the other sections. It could be a simple vertical stack but is more often a combination of several components. A typical system includes an augmenter tube followed by a water cooling system and, possibly, a diffuser. Downstream from the diffuser there may be acoustic splitter paneling, lined walls, or right-angle bends. Associated with the bends there could be turning vanes or flow directing fins of various sorts. Some fins may even be water cooled. In the portion of the exhaust stack where the exhaust flow has been turned upward might be lined ducts (single sections or multiple sections), paneling, or a tortuous-path (labyrinth) for noise suppression.

A. Test Section

The design of the test section or engine room is determined by the specific function of the cell. A basic requirement, of course, is that the engine room be capable of accepting the engine for control, adjustment, and repair. Some cells house the complete aircraft, and some merely cover the aircraft intake and exhaust sections; but most test cells house just the engine.

For safety reasons the engine room normally contains only necessary handling equipment, instrumentation, and an engine mount or thrust stand. Accessibility for engines and equipment is generally facilitated by large power-operated doors. Personnel access to the engine room is provided by smaller doors. Engine room operation is usually monitored through observation windows, but some more elaborate facilities utilize closed circuit television.

B. Intake System

Various types of intake systems cause different amounts of cell depression, airflow turbulence, secondary air velocities, room temperature variations, and sound attenuation. The most important attenuation function of the intake treatment is the reduction of noise in the higher frequency bands as associated with engine compressors.

The most common type of intake treatment is the lined duct. When greater attenuation is required, parallel baffles or even serpentine panels are used. On occasion, the intake system consists of one or two lined bends in conjunction with lined ducts.

Separate secondary airflow intakes have been incorporated into many cells. The inlet for this special secondary airflow is generally located near the engine nozzle position or somewhat downstream from the engine nozzle. Augmenter or ejector action provides the pumping or driving force for this airflow.

Acoustic treatment of secondary air paths or ducts can be an absorptive lining, splitter panels, lined bends or any combination of these.

The amount of intake duct airflow is the major controlling factor of the dynamics of the engine room. This airflow dictates cell depression and, to some extent, cell airflow velocity and temperature.

The placement of the air intake in relation to the engine inlet bellmouth is also an important factor in engine-room dynamics in that proper airflow from the intake duct system can avoid undesirable turbulence in and near the engine inlet. This is discussed in detail in Section IV.

C. Augmenter Tube

One of the most vital parts of the test cell design is the augmenter or ejector tube. The hot engine exhaust and the cooler secondary air are collected, mixed, and channeled by the augmenter into a sound-treated evacuation or exhausting system.

Since the augmenter configuration, together with the engine operating conditions, controls the volume of pumped secondary air, the augmenter design is determined by the volume flow (or velocity) and temperature restrictions of the exhaust system. Augmenter tubes, therefore, are usually designed in conjunction with water cooling systems (spargers) and diffusers because these devices play such an important part in producing the required velocity and temperature environment in the exhaust system. The proper relationship between weight of primary gas flow, secondary air and amount of cooling water, when used, must be established to assure acceptable final temperatures and flow conditions within the suppressor. Water spargers and diffusers sometimes tend to block the flow, so total flow areas through these devices must be kept large enough to maintain an adequate flow rate.

Proper augmenter cooling system design and diffuser design are discussed at length in Section IV.

D. Exhaust Plenums and Turning Vanes

Aft of the augmenter tube, the hot exhaust gas may expand into a chamber (the exhaust plenum) which provides a flow velocity reduction prior to a flow redirection. Devices can be installed here which distribute the flow evenly through the exhaust treatment. In addition, the exhaust plenum provides for some energy absorption; that is, generated acoustic energies at some frequencies can be dissipated by resonances in this chamber. Several plenums or expansion chambers (Reference 4) may be utilized by placing acoustic treatment such that intermittent open volumes occur. Some of these acoustic designs are discussed in Reference 2, Section IV and Appendix C.5.

Turning vanes are used advantageously when the exhaust flow is to be turned upward in a 90-degree bend. Their primary purpose in this instance is to extend the useful life of the exhaust-stack acoustic treatment by evenly distributing the exhaust flow through the stack. For, where a concentration of airflow exists, the fibrous acoustic treatment of the panels may be eroded and the metal warped or deformed. Once the metal starts to warp, or the panel to erode, these deformations become even more sensitive to further distortion. Because of the high-temperature environment, turning vanes are usually constructed of heavy steel plate or, sometimes, even stainless steel.

E. Exhaust Stack Acoustic Treatment

The exhaust stack treatment is a vital noise reduction component, but its acoustic effectiveness is sometimes complicated by its influence on the aerodynamic and thermodynamic operation of the cell.

As in the case of intake duct design, the pressure drop through the exhaust treatment must be considered. Adequate design of the exhaust treatment provides for a gradual pressure drop throughout the flow path. Abrupt narrowing of the flow area, if too extreme, will act to increase the pressure. The pressure drop through the entire exhaust treatment is usually of a higher magnitude than through the intake system.

If the flow area through the exhaust stack is too small, and the pressure therefore increased, the velocity through the stack will likewise be increased. Furthermore, a regeneration of noise can occur at the plane of the exhaust stack outlet due to high, turbulent, exit velocities.

The velocity limitation of the flow through the noise reduction system, then, determines the life span of the system and, to some extent, the very ability of the system to reduce noise.

In some cases, where exhaust stack height is restricted and it is thus not possible to use the required length of lined duct or parallel baffles to obtain the necessary noise reduction, serpentine panels or labyrinth treatments might be used. These devices have the effect of lengthening airflow and noise-propagation paths when the height is limited. A labyrinth treatment is shown in Figure 1. As can be seen, the flow traverses several turns before it is ejected out into the atmosphere. These turns are usually lined and are effective in silencing the higher bands of the audio frequency range. Other typical exhaust sound treatment systems are presented in Figures 2 and 3.

Some exhaust systems may have expansion cones at the exit end of the exhaust treatment. These exhaust expansion systems serve in a small way to reduce flow velocities at the exit end of the treatment and thus reduce the effective regeneration of noise. They may also provide some pressure recovery for the hot gas flow.

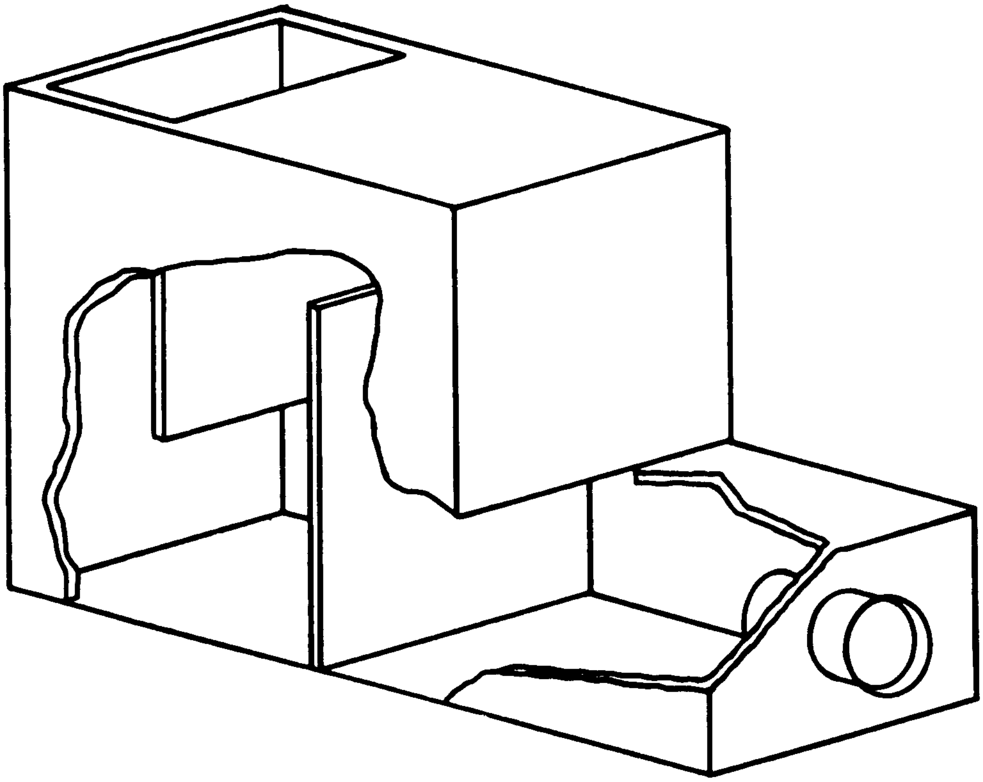


Figure 1. Example of Labyrinth Exhaust System

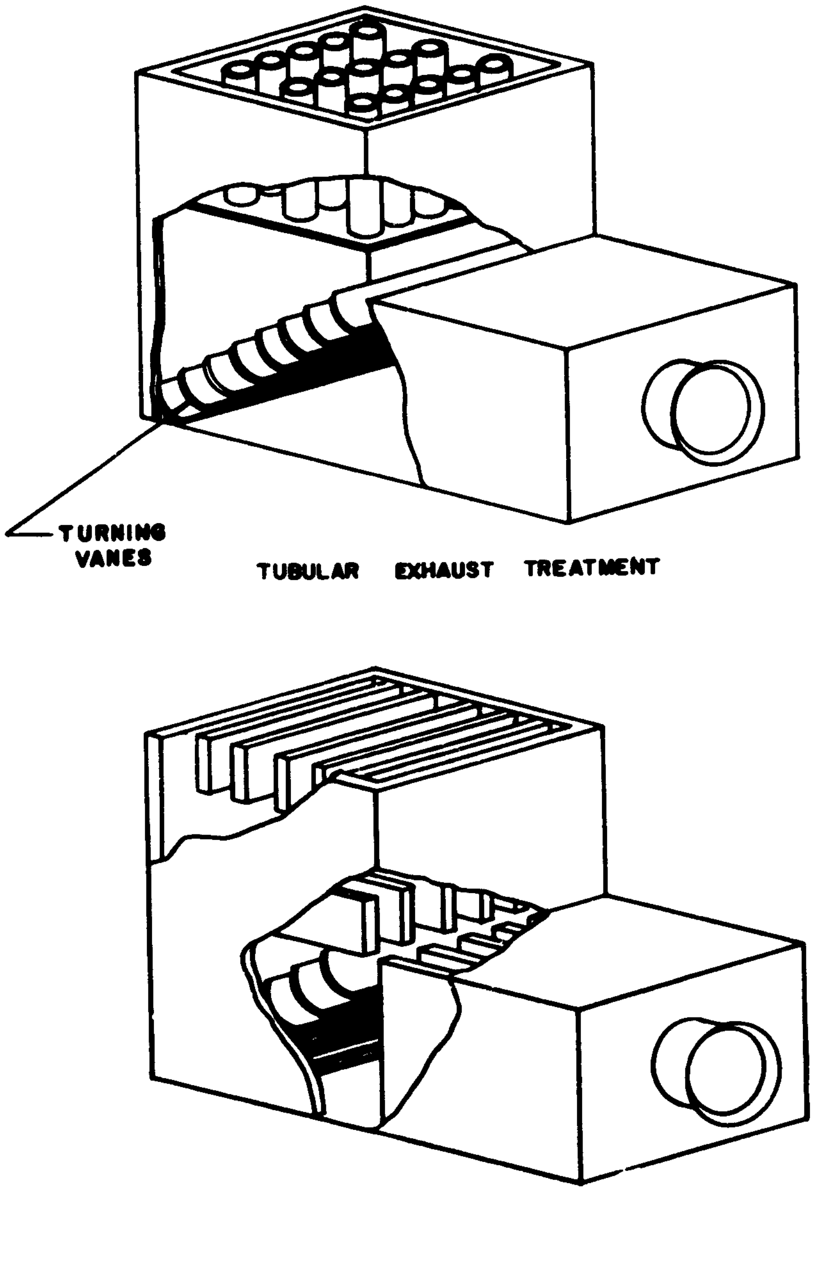
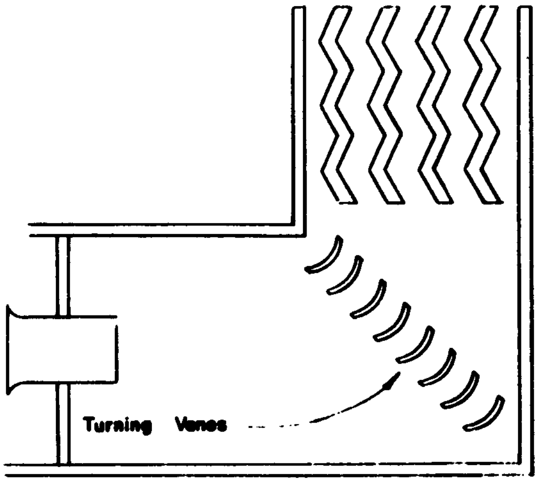
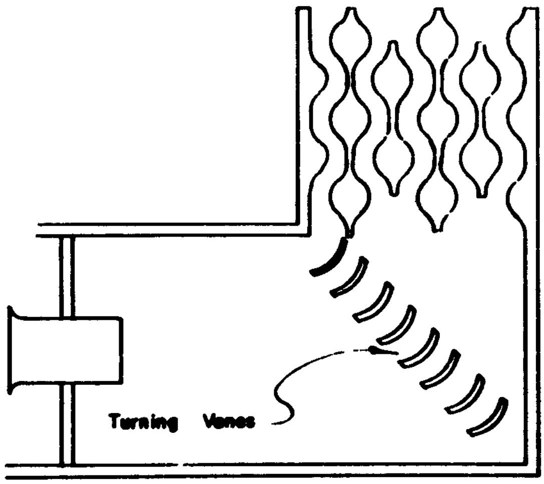


Figure 2. Multiple Section Exhaust Treatment



SERPENTINE EXHAUST TREATMENT



SOUNDSTREAM EXHAUST TREATMENT

Figure 3. Tortuous Path Exhaust Treatment

DEFINITION OF ENGINE PERFORMANCE

Ground run-up operations of turbojet engines are performed to permit close observation of engine functions. Engine operation observation aids the repair or readjustment of the engine and permits final verification of its correct operation.

When a turbojet engine is operated within the confinement of a portable suppressor or a complete test cell, the atmospheric environment of the engine may be altered significantly from open field conditions. Significance of environmental alteration is measured by the magnitude of the influence that the environment has upon engine operation. This Section will be devoted to a discussion of the engine parameters which are affected by changes in environmental conditions.

The turbojet engine recognizes a change in the altitude or, more specifically, the pressure condition at the inlet to the compressor and changes in the pressure condition affecting the pressure distribution over the area of the exhaust nozzle. It is possible that these environmental conditions could alter the engine's capabilities to produce a design thrust or a desired thrust. How these external conditions affect the internal engine functions will be considered here.

Occasionally, the environment within a test cell or ground run-up facility will interfere with the correct measurement of engine operating conditions. Both the direct influence on the production of thrust and the secondary influence of instrumentation error caused by environments can impede ground run-up operation. These effects will be discussed.

Some primary engine functions are described in order to provide a fundamental recognition of jet engine operation. Since each type of turbojet engine will have somewhat different operating conditions, only a general discussion will be presented. Figure 4 shows typical internal pressure variations throughout a turbojet engine. The data shown summarize information obtained from wind tunnel tests during prototype development and from an accumulation of engine manufacturers' test information. The values of parameters such as thrust, RPM, ram pressure, etc., are presented to give the reader an idea of the empirical data that may result from turbojet engine testing. However, these data should not in any way be used as ideal or all-inclusive operating conditions.

As each engine is designed or adjusted to provide an optimum performance under load conditions it is mandatory that engine manufacturers' operating instructions be followed implicitly to obtain peak performance. All engine manufacturers provide detailed operational handbooks for their particular engines. These handbooks, of course, should be referred to prior to cell operation. They should also be referred to prior to the design of test cells intended for specific engines.

A. Effects on Engine Performance

The primary reason for consideration of test cell depression is that it imposes altitude pressure conditions upon jet engine operation. As engine performance is determined by the relationships between such engine parameters as compressor rotational speed, thrust, mass flow, and fuel flow, discussions concerning test-cell depression effects on engine performance should consider these relationships. Normally, if the test cell depression is low (i.e., cell ambient pressure is close to standard-day conditions), no altitude correction need be applied to the performance data. The effect of high altitude (low pressure) on engine performance may be observed in the plot of Figure 5. These data show a typical example of how compressor efficiency varies with increasing altitude.

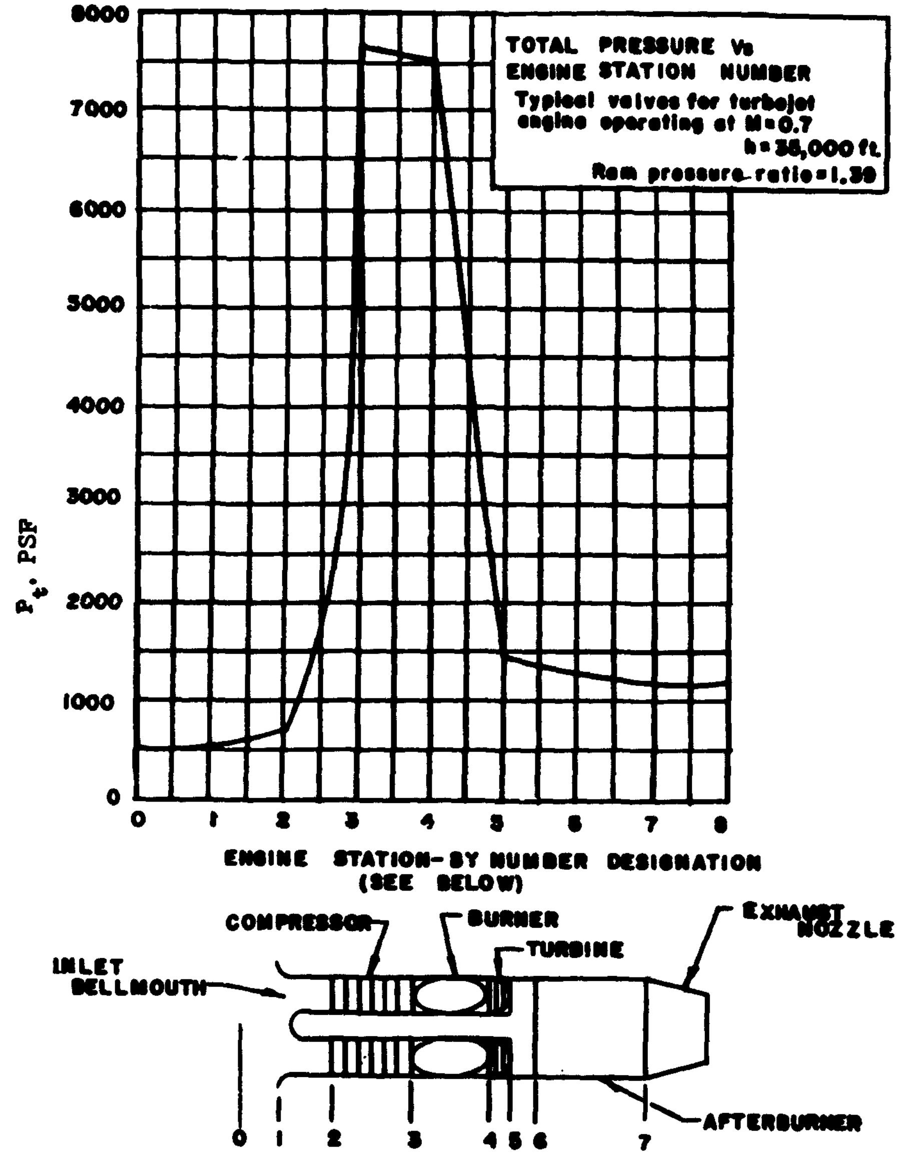


Figure 4. Typical Turbojet Engine Internal Pressure Variations

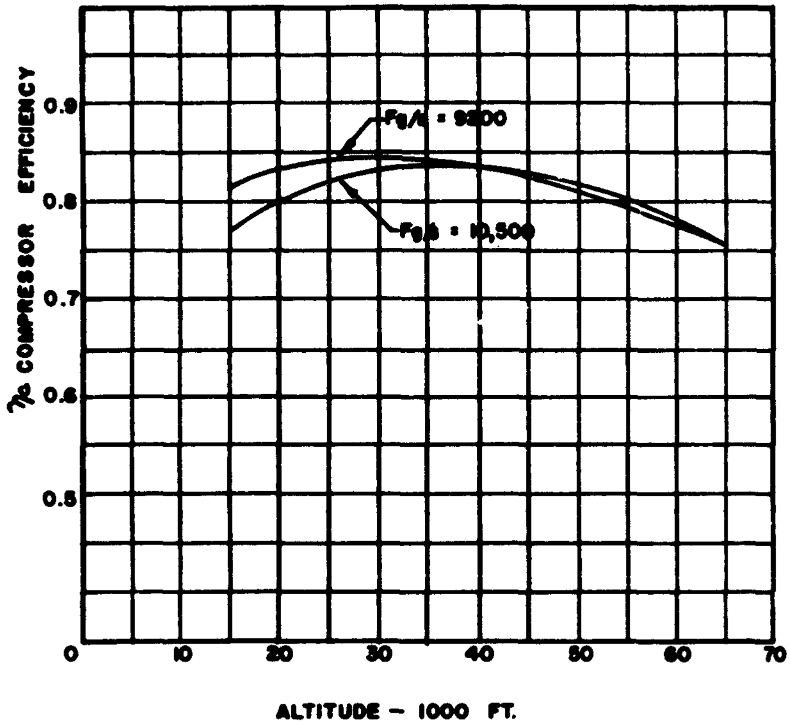


Figure 5. Compressor Efficiency Versus Altitude for Engine Operating at M = 0.9 (Ram Pressure Ratio = 1.7)

Figures 6, 7 and 8 show the generally accepted response curves or relationships of corrected engine speed to corrected thrust, corrected mass flow, and corrected fuel flow, respectively. These data were obtained from test chamber measurements during the development of a 10,000- to 12,000-pound thrust turbojet engine. Engine manufacturers normally provide a set of performance curves, such as shown in these figures, with an engine. Performance curves are usually for the engine as operated in a free field (outside of any restrictive structure) at sea-level standard-day conditions.

To accomplish the initial evaluation of a noise suppression facility, it is advisable to first operate the engine in the open, away from the cell. Measured performance will verify the engine manufacturer's curves and provide a basis for comparison when the engine, or a similar engine, is operated within the confines of the cell.

A fourth relationship showing engine performance responses which indicate the influence of cell conditions is the tailpipe-total-pressure versus thrust-response curve. See Figure 9. One engine manufacturer feels that a thrust-versus-RPM relationship does not always vary consistently when the engine is operated within a test cell (Reference 5). He feels, therefore, that using the tailpipe pressure-inlet pressure ratio rather than the thrust indication does provide more information concerning engine operation. Since tailpipe pressure is an engine parameter normally monitored, frequent comparisons between thrust, RPM and this pressure ratio should be made.

Another indicative engine parameter used to compare engine operation in and out of testing facilities is "specific fuel consumption". This parameter is computed from fuel, time, and thrust measurements and is expressed in pounds of fuel consumed per hour for each pound of thrust delivered. As each engine has an operating range of specific fuel consumption, it will be the aim of the engine operator to keep this at a minimum for optimum performance.

B. Engine Performance Corrections

Correcting the thrust, exhaust flow, and fuel flow to standard-day sea-level conditions requires applications of constants to the measured values at the altitude conditions imposed by the cell. The following equations are utilized when applying these corrections:

Thrust at NACA Standard sea-level atmosphere $= \dfrac{F_g}{\delta_{t_1}}$

Mass flow at NACA Standard sea-level atmosphere $= \dfrac{W_g \sqrt{\theta_{t_1}}}{\delta_{t_1}}$

Fuel flow at NACA Standard sea-level atmosphere $= \dfrac{W_f}{\delta_{t_1} \sqrt{\theta_{t_1}}}$

RPM at NACA Standard sea-level atmosphere $= \dfrac{n}{\sqrt{\theta_{t_1}}}$

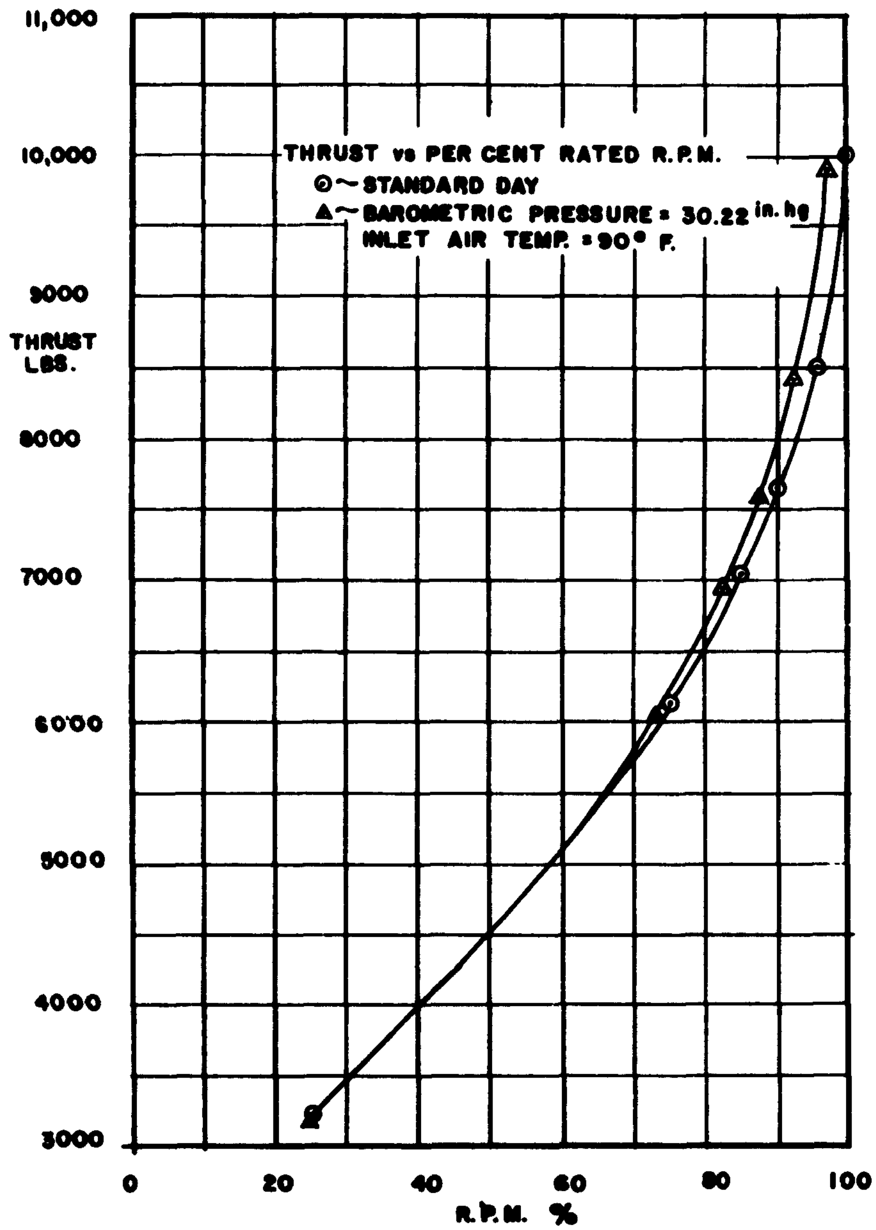


Figure 6. Corrected Thrust Versus Corrected RPM

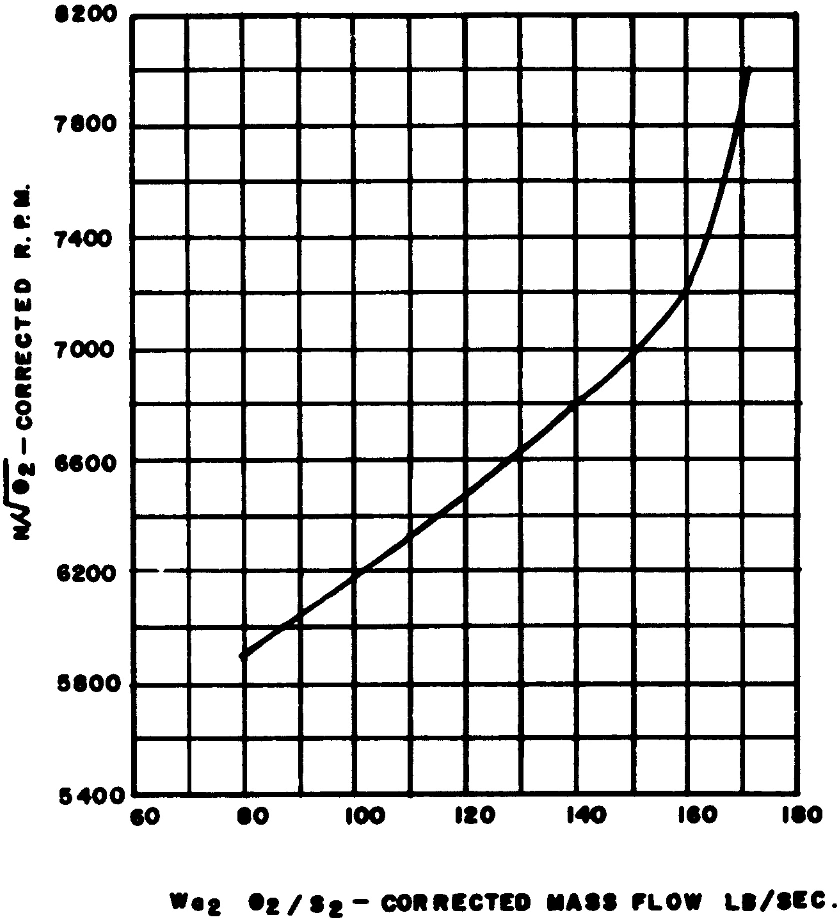


Figure 7. Corrected RPM Versus Corrected Mass Flow

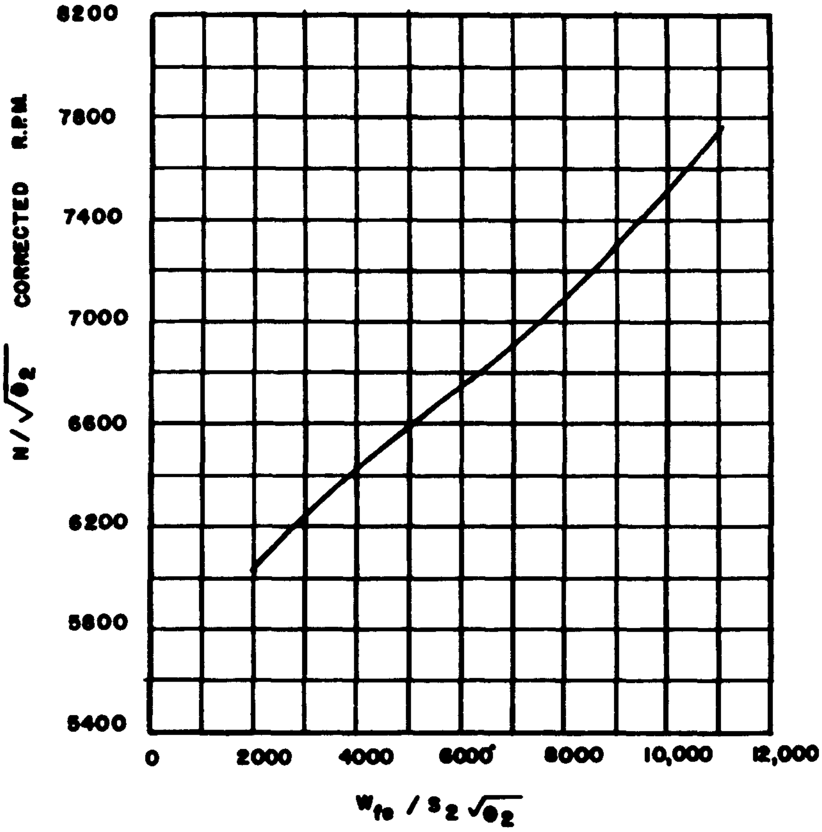


Figure 8. Corrected RPM Versus Corrected Fuel Flow

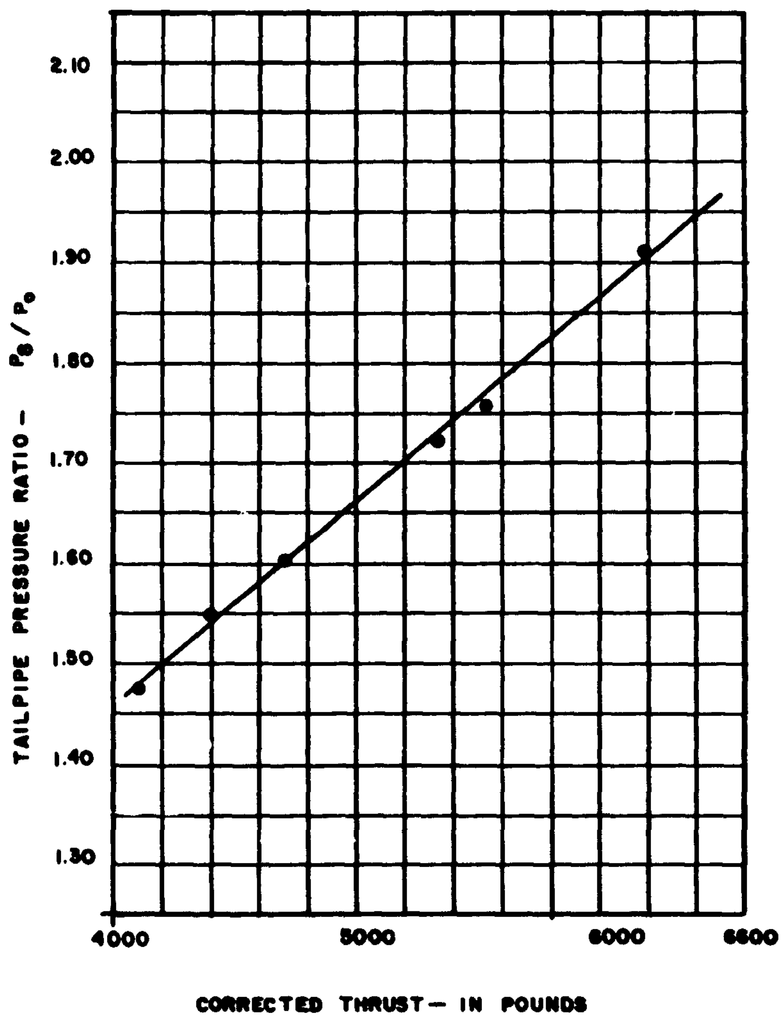


Figure 9. Pressure Ratio Versus Thrust

where

F_g = measured thrust

W_g = measured mass flow

W_f = measured fuel flow

n = measured RPM

and

$$\theta_{t_1} = \frac{T}{T_o} = \frac{\text{absolute temperature at test location}}{\text{absolute NACA Standard sea-level pressure}}$$

$$\delta_{t_1} = \frac{P}{P_o} = \frac{\text{ambient pressure at test location}}{\text{ambient NACA Standard sea-level temperature}}$$

Tables 1 and 2 of Appendix E provide most of the necessary values of $\frac{1}{\delta}$, $\frac{1}{\theta}$, and $\frac{1}{\sqrt{\theta}}$ for engine parameter calculations and corrections.

Test cell depression may have some slight effect upon the response curves shown in Figures 6, 7 and 8. Usually in the upper range of thrust and RPM there is less effect. The effects that are found are outside the normal altitude correction influences.

The efficiency of the turbojet engine increases with air speed. As an engine pushes its way through the atmosphere a ram effect causes a pressure build-up or increase at the inlet to the compressor. This increase in pressure is desirable, since it allows a greater compressor outlet pressure. This condition, in turn, provides a greater potential energy availability for the burning and exhausting process.

It is not normally intended that individual corrections be isolated as to test cell depression and augmenter effects. In the evaluation of the test cell these effects are combined by testing the jet engine inside and outside the test cell.

Additional influences that inhibit accurate engine performance evaluations are instrumentation errors and engine room velocity effects external to and parallel to the engine. See Appendix A. Recommended cell and engine instrumentation is discussed in Section VI.

A correction factor must be applied to the measured thrust when the velocity through the cell past the engine becomes great enough to cause the correction factor to exceed 1 percent or to exceed the accuracy of the engine instrumentation. See Section V.B.2. The ram pressure correction factor $\mathcal{N}$, can be calculated using Equation (9) of Appendix A. For use here the equation can be rewritten as

$$\mathcal{N} = 1 + 0.2031(2R+1)K \qquad \text{(III-1)}$$

where

$$K = \frac{\left(\frac{W_p \sqrt{\theta}}{\delta}\right)}{A_t \left(\frac{F_g}{\delta}\right)} \qquad \text{(III-2)}$$

The plots in Figure 10 show the ram pressure correction, ν, plotted against this factor K for five values of the pumping ratio, R.

Section V.B.2 describes considerations for limiting the ram-pressure correction factor during test cell design.

The most significant design factors to consider when finalizing engine room configuration are cell depression and engine inlet flow.

The need for smooth laminar flow at the compressor inlet cannot be overemphasized.

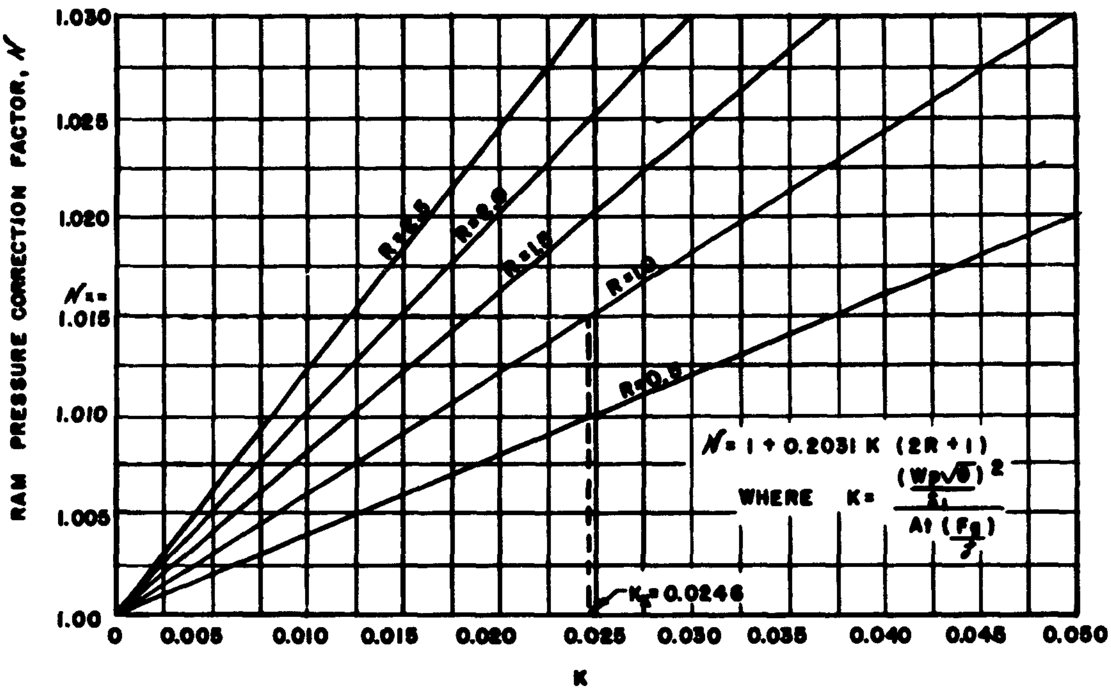


Figure 10. Ram Pressure Correction Factor Versus K

SECTION IV

AERODYNAMIC AND THERMODYNAMIC CONSIDERATIONS

Early engine test cells may have been designed initially to provide shelter against adverse weather conditions. Eventually, however, the need for noise reduction facilities became apparent. Larger, more powerful engines and a greater usage of these engines made test operation more irritating both to test personnel and to neighboring communities. The early open-ended type shelters presented no aerodynamic or thermodynamic restrictions to the engine being tested. But once enclosed completely, with intake and exhaust flow restrictions (acoustic treatment), the engine was made to operate in an environment that was not always normal. That is, the environment might cause the engine to respond differently from its open-field response. To avoid this condition, the early trend in cell design was just to make the cell large, providing unrestricted flow. However, many cells have been constructed, and are still being used, that do affect the engine operation aerodynamically and thermodynamically.

In recent years more consideration has been given to the aerodynamic and thermodynamic design of cells, but deficiencies are still frequently found in new constructions.

It has been determined in cell correlation tests that a given engine operating at identical power ratings in several different test cells may result in measured performances which are considerably different.

Engine operating deficiencies, if they exist, must be pinpointed during cell run-up. These deficiencies should not be hidden by the environmental influences of the testing facility. In other words, the cell environment must impose a minimum influence and that influence must be accurately defined.

It is the purpose of this Section to furnish the operating engineer, the test cell designer, and the test-cell specification writer with information concerning the performance of test cells relative to the performance of turbojet engines with the test cells.

The cell designer must be aware of the composite requirements of the testing facility. The designs of the various components are interrelated. Overall results of the various components must be evaluated before final design conclusions are made. For instance, cell depression is only one consideration. For each engine tested, the designer must know the engine mass flow, the inlet pressure requirements, the secondary pumping air requirements, the maximum exhaust velocity, and the maximum mixed gas temperature allowable in the exhaust system. All of these factors are of primary concern when considering the composite design.

A. Cell Depression

Because of their design, some test cells have no perceivable effect upon jet engine operation. Such cells have very low intake air velocities, low engine room velocities, and low cell depression.

The instrumentation needed to assure valid testing, permit trim or pre-flight adjustments and parameter measurements are discussed in Section VI-J.

In one installation the maximum allowable depression may be only 10 lb/sq ft (2 in. of water), while in another installation it may be 62 lb/sq ft (12 in. of water). The pressure resistance characteristics of the cell walls are usually much greater than the pressures imposed by the cell depression. Most reinforced concrete cell walls of approximately 12 inch thickness withstand pressures of from 150 to 300/lb/sq ft. Further discussion of cell walls is contained in Section V-B.

1. <u>Cell Depression Comparisons Between Facilities</u>

It is necessary to convert operating performance parameters to some standard pressure and temperature so that a comparison can be made between tests in cells at various geographic locations or with various values of cell depression. Composite cell design should supply balanced operational inlet and exhaust flow conditions which can be corrected to standard-day values.

Correcting engine performance to standard atmospheric sea-level conditions (temperature = 59°F, pressure = 29.92 in. of Hg) will produce engine test results than can be compared directly to the ideal operating conditions set for the engine by the manufacturer. Equations for correcting engine performance are presented in Section III-B.

2. <u>Intake Size Determination</u>

The design of the intake noise suppression system is determined by the allowable pressure drop between the outside ambient pressure and cell pressure. It is desirable to use a straight-through type noise suppression intake treatment with a resulting low pressure drop. Such treatment may be provided with lined ducts or parallel baffles.

The equation that permits the prediction of the approximate pressure drop through such treatment due to the flow velocity is derived from

$$v_1^2 = 3 \Delta p \frac{T_a}{459 + T} \times 10^3$$

where

v_1 = intake velocity, ft/sec

Δp = pressure drop, inches of H_2O

T_a = absolute temperature, degrees Rankine

t_a = average ambient temperature, 59°F

459 = absolute zero, degrees Rankine

Hence, the pressure drop becomes

$$\Delta p = \frac{v_1^2}{3} \frac{459 + T}{T_a} \times 10^{-3}$$

or

$$\Delta p = \frac{518}{3} \frac{v^2}{T_a} \times 10^{-3} \quad \text{for } T = 59^\circ F$$

Thus

$$\Delta p = 0.173 \frac{v^2}{T_a} \tag{IV-2}$$

When a reduction in cell depression is required for an existing cell, it will be necessary to reduce the velocity through the intake system. Figure 11 shows four different intake treatments and bend arrangements that may be used. The pressure drop, when intake bends are used, will be approximately 2/3 in. of H_2O for each 90-degree turn.

Mass flow of primary air will vary with the type of engine being tested. Thus, the total mass flow of intake air, which includes both primary and secondary air (for a cell with a single intake system), will vary with the engine and with the secondary air pumping requirements. Figure 12 shows how the cell depression may vary with mass flow for several pumping ratios and a given intake system opening size. The curves of Figure 12 were derived for a cell with an intake system opening of 100 sq. ft. Cell depression was determined using Equation (IV-2) after the velocity was found from the general continuity equation:

$$V_i = \frac{W_i}{A_o \rho_{air}} \tag{IV-3}$$

and

$$W_i = W_p \quad (1 + R) \tag{IV-4}$$

and where

V_i = volume flow

A_o = intake system opening area

W_i = intake mass flow, total

ρ_{air} = density of outside ambient air or 0.076 lb/ft^3 for standard day conditions

W_p = primary mass flow of engine

R = pumping ratio of secondary air (mass flow) to primary air (mass flow)

Ideally, the velocity through the intake treatment should be kept low. However this may not permit the most economical construction. To lower the velocity, the percentage of open area through the intake treatment is made greater. This means that large quantities of acoustic treatment must be furnished, either to line the ducts and bends or to be used as baffles. The expense of the treatment increases, of course, with the physical volume of such treatment. The cell designer should determine the maximum amount of cell depression permissible. The intake treatment system should then be designed such that the average intake velocity at maximum engine operating conditions, plus any pressure drops caused by bends in flow, does not create cell depression beyond that permissible maximum. Figure 13 shows the relationships between pumping ratio, intake opening size, and cell depression for a 270 lb/sec mass flow turbojet engine. Pressure drop due to bends should be added to these data.

3. Mechanical Regulation of Cell Depression

Some existing cells have a throttle valve arrangement (usually a sliding door) which controls the flow area of the intake system. In this way, the velocity through the intake system may be adjusted, thereby regulating cell depression. In such facilities, the opening is best adjusted to the maximum allowable cell depression dictated by best operation of a specific engine. Standard pre-set correction factors for a given cell depression can then reduce the number of separate calculations that must be performed for engine evaluation.

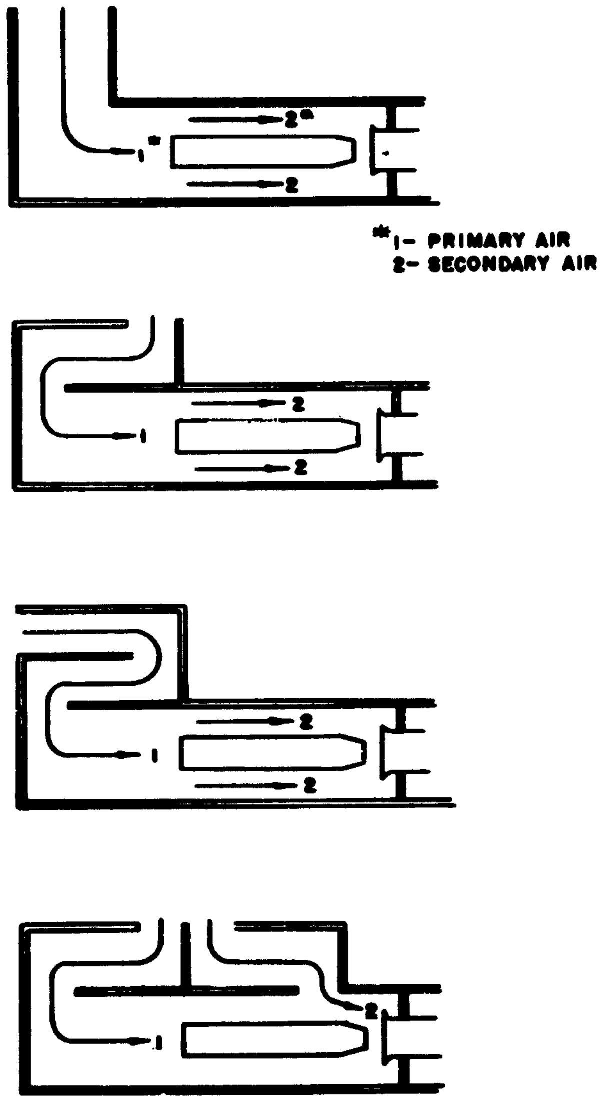


Figure 11. Four Intake Bend Arrangements

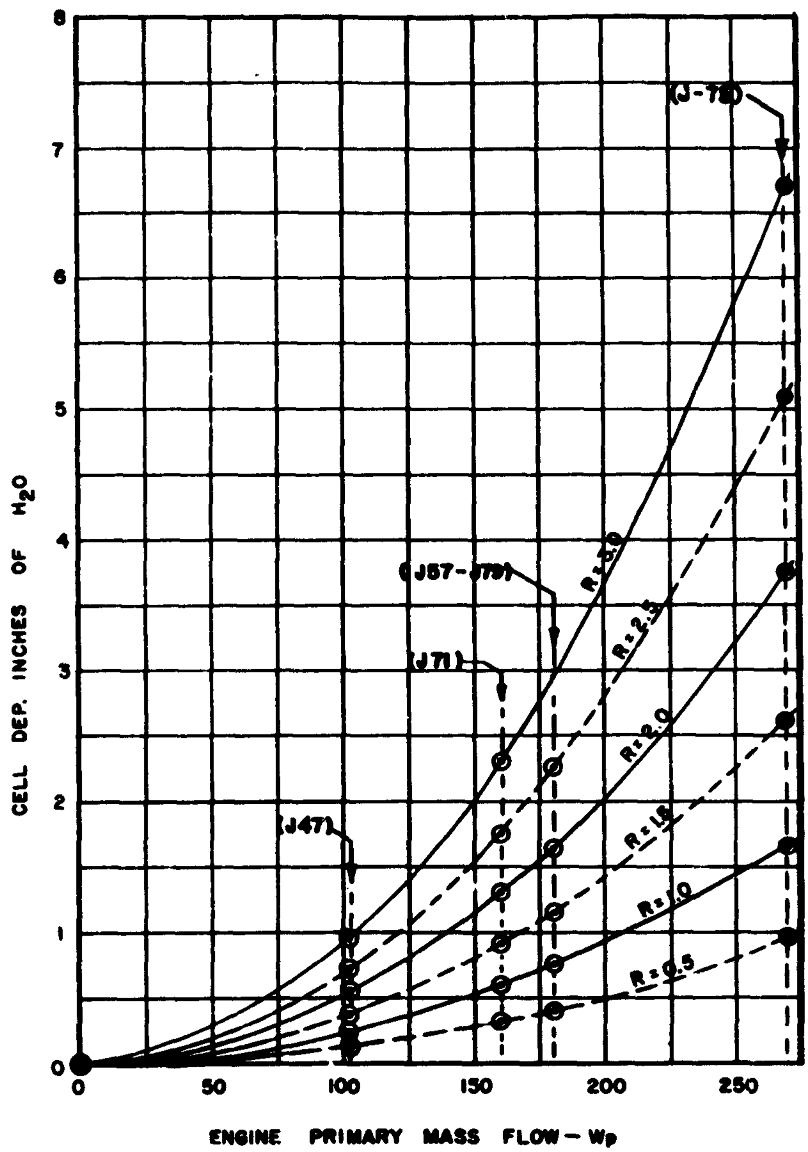


Figure 12. Cell Depression Versus Mass Flow

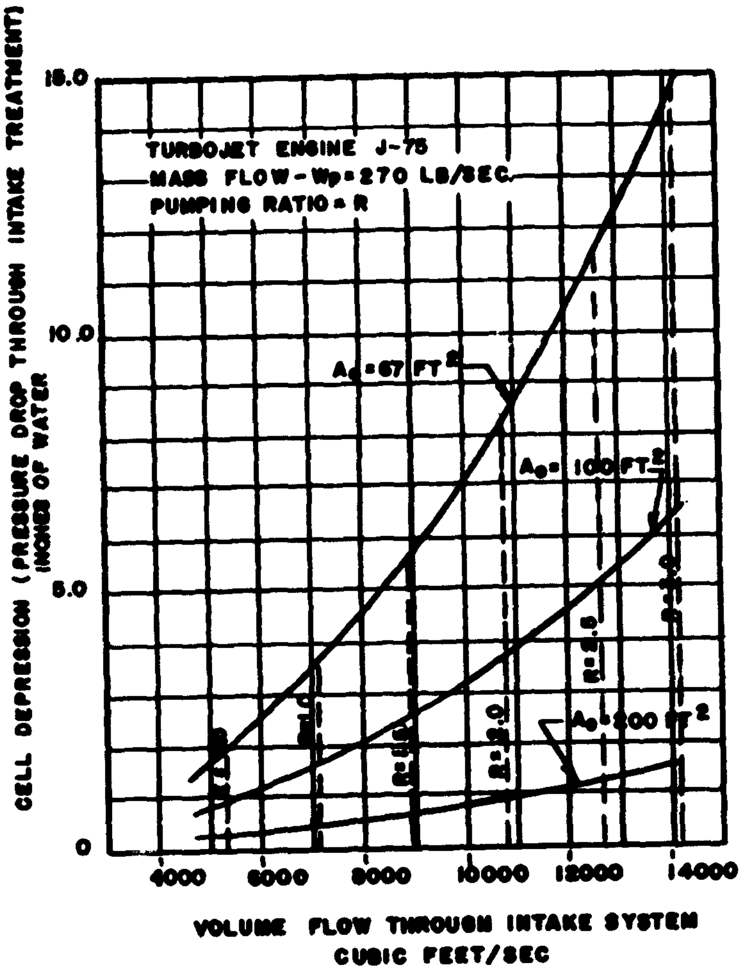


Figure 13. Cell Depression Versus Intake Volume Flow

Sometimes a safety device is used to prevent cell depression from exceeding the maximum value. When cell depression reaches the maximum allowable conditions, the engine RPM will be reduced automatically or, in some extreme cases, will be shut off. Such systems provide precautionary measures for protection of the testing facility and thus prevent an engine from operating in a detrimental environment.

B. Pressure Distribution

One of the most critical influences which the test cell structure has upon the performance of the turbojet engine is that caused by pressure gradients across the engine inlet. Pressure differences across the engine inlet bellmouth may be caused by nonsymmetrical channeling of the intake airflow from the intake ducts to the engine.

1. Necessity of Smooth Intake Airflow

The intake of the cell, at least in the vicinity of the bellmouth, should be uniform and gradually contoured. Wall protuberances or indentations should be avoided. Sharp turns or abrupt changes in the direction of flow should be avoided.

Turbulent engine inlet flow conditions can be minimized by proper cell design. Cell intake openings must be properly aligned with the bellmouth to prevent an irregular airflow path to the engine inlet. It is a good policy, in cell design, to make the engine room large enough to provide ample space between the intake duct (which is usually at right angles to the engine inlet) and the engine inlet. Enough separation distance should be obtained to provide essentially laminar flow at the engine inlet bellmouth. Where possible, the distance from the engine inlet bellmouth to the intake system should be at least equal to the height of the cell room. When a shorter distance is required between the intake system and the inlet bellmouth, it will probably be necessary to install ceiling baffles (partial partitions). In some instances, these can be added to existing cells to improve airflow to the engine. See Figure 14.

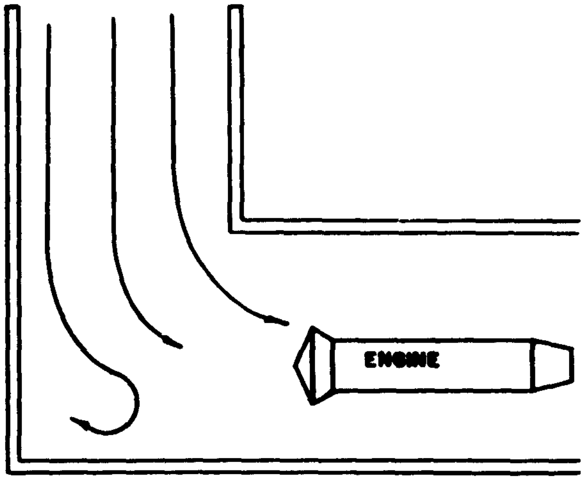
The intake treatment that is horizontally in line with the engine centerline gives the smoothest airflow. However, this type of intake treatment is costly because of the number of panels required for adequate noise reduction. A vertical stack is most often used because of its noise reduction capabilities. Redirection of the noise upward and sound absorption at bends are its acoustical attributes.

A schematic presentation of temperature, pressure and velocity throughout an entire cell is provided in Figure 15. Particular notice, here, should be made of the typical operating conditions for the intake and cell room positions. The cell shown in the figure is the most widely used configuration. In extreme cases where space and height limitations restrict the design, double or even side intake ducting is used. Workable airflow patterns within the cell can be found, but it is recommended that model flow studies be made before design finalization. One such extreme design problem, illustrated in Figure 16, was solved by model studies. The resulting cell room actually had excellent airflow (Reference 6) and proved to have low correction factors.

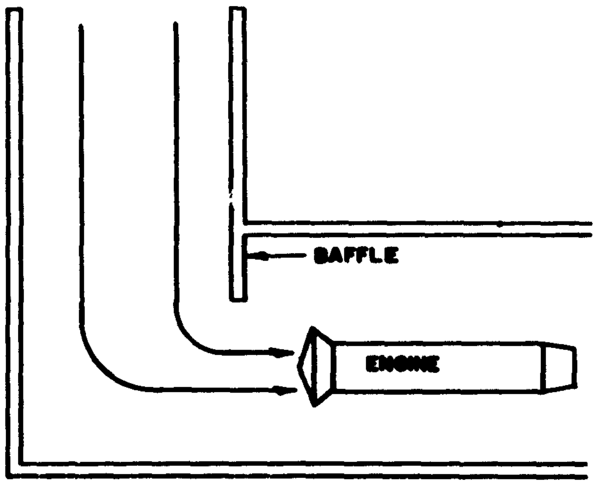
2. Distortion Effects on Engine

In order to determine what effect poor inlet velocity distribution has upon engine performance, the inlet area was purposely distorted in one set of tests (Reference 6) by applying various meshes of screen in assorted patterns. It was found that a variation of as much as 5 lb/sec mass flow and 500 lb thrust reduction occurred.

Aside from the obvious detrimental influences on engine operation, other more serious effects can result from poor inlet flow distributions. Engine starts can be more difficult and operation may approach the stall condition. Such conditions can cause damage to the engine.



A. POOR INLET FLOW CONDITION



B. EFFECT OF INTAKE CEILING BAFFLE

Figure 14. Cell Side View - Intake System
A. Poor Inlet Flow Condition
B. Effect of Intake Ceiling Baffle

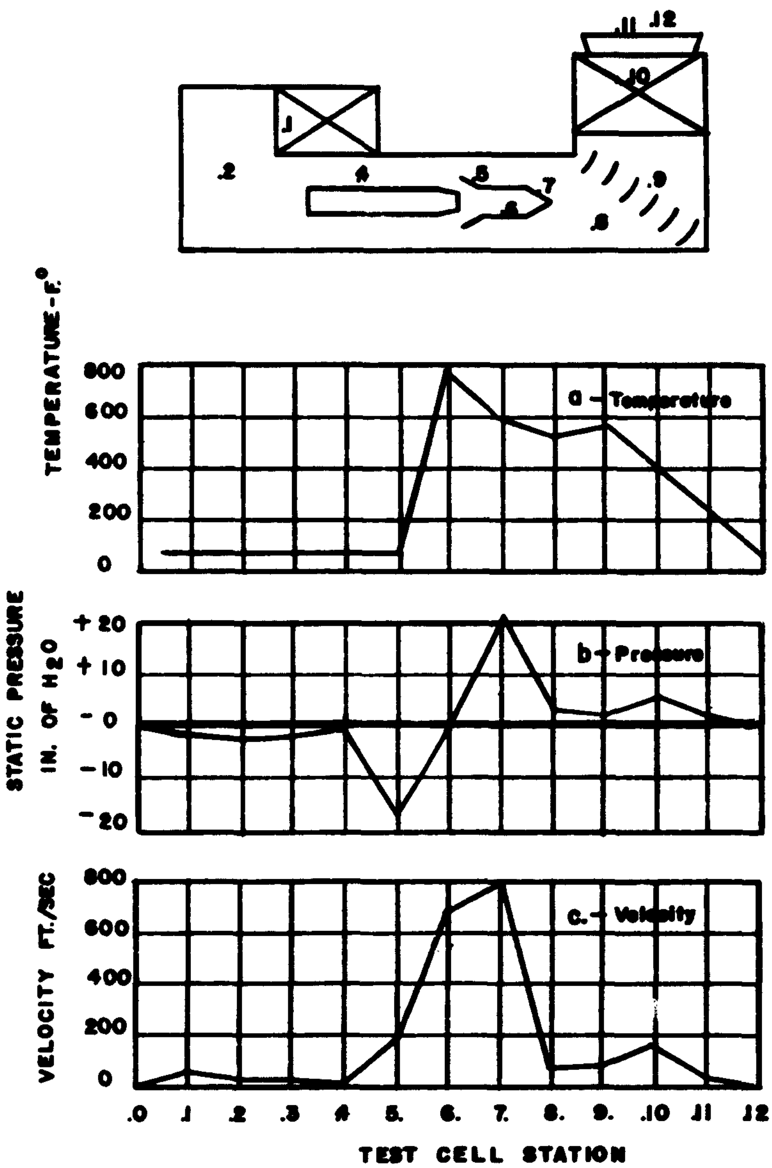
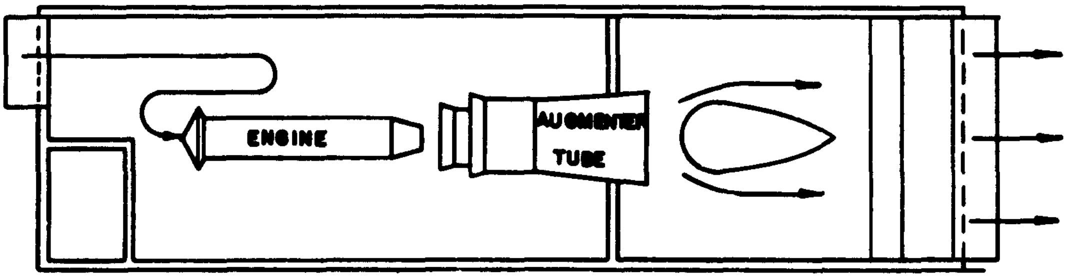
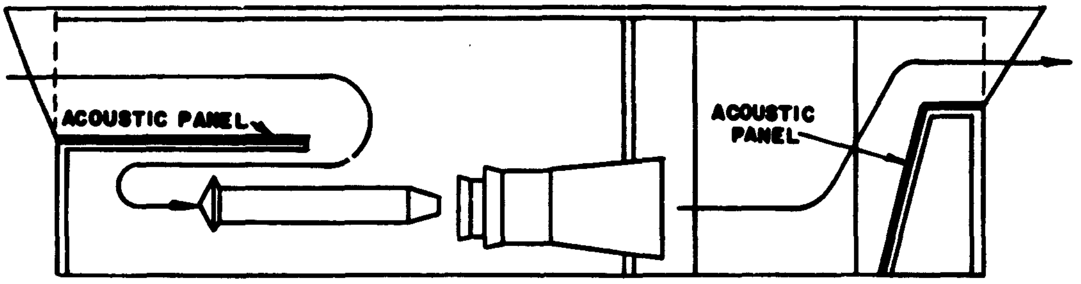


Figure 15. Cell Parameters Versus Station



PLAN VIEW



SIDE VIEW

Figure 16. Cell 13 (North Island)

The velocity distribution imposed upon the inlet during the above mentioned tests did not normally fluctuate with time. A somewhat different condition exists when cell flow turbulence occurs. The variations experienced in these tests may be magnified many times if the distortion is of a fluctuating nature (i.e., the variations move from quadrant to quadrant, out and in radially, or vary in magnitude).

3. Engine Room Airflow

a. Fluctuating Airflow. Improper airflow in the engine room is not limited to the pressure buildup type of flow condition. The opposite condition of too much augmenter tube pumping may be a deterrent to obtaining correct engine performance testing. As with back pressure, an unwanted influence upon engine thrust measurement is experienced.

Oscillating tendencies of turbojet engine operation may make the cell airflow conditions unstable. This could result in unreliable engine performance measurements.

Equations for predicting cell airflow are derived in Appendices B and D.

In considering a design for a new test cell, it is wise to plan for the largest engine for which the cell might possibly be used. A few extra feet in width and height presents additional costs for new cell constructions, but that cost is small compared to modification costs if the cell has to be changed or enlarged later for the larger, more powerful engines.

b. Secondary Air Pumping. If too much pumping occurs at the augmenter tube inlet, the pressure at the exhaust nozzle will be lower than at the engine inlet bellmouth. A difference in pressure acting upon opposite ends of the engine can result in a tendency to move toward the lower pressure. When a high secondary air inlet velocity occurs, the lower pressure becomes significant and will result in inaccurate (lower) thrust indications due to the pressure differential and the drag of the high velocity air past the engine. When exhaust pressure increases, due to improper or insufficient flow through the augmenter tube, a reverse pressure difference may be observed between the exhaust nozzle and the engine inlet bellmouth. When the pressure at the exhaust nozzle is higher (smaller negative value), the resulting force appears to act in a direction away from the augmenter tube. This force is then additive to the thrust of the engine as it acts in the same direction upon the engine structure. Again, this condition will interfere with the true measurement of engine thrust.

Ram pressure effects upon engine operation are discussed in Appendix A.

Ideally, new test cells should be designed to provide the minimum amount of overall pressure influence on the engine. However, in existing cells, either of the aforementioned conditions may exist. If they exist and no immediate correction is available, it is possible to determine the magnitude of the influence and apply corrections to thrust measurement to obtain valid engine performance testing. Obviously, it is impossible to operate an engine in a cell where back pressures become significant enough to return hot gases to the engine room. Back pressures, here, can be described as those pressures which occur well within the augmenter tube, resulting in an impairment of flow at the augmenter inlet. Adequate secondary air pumping is a primary factor to consider in providing a balanced cell design.

Detailed pressure-temperature measurements must be made in the vicinity of the engine inlet bellmouth and the exhaust nozzle. A determination of the secondary airflow is also required. The use of these pressure measurements in correcting engine performance has been described in Section III.

4. Engine Oscillation Relationship to Pumping

In the evaluation of the dynamics of a given test cell, the engineer should be aware of the possibility of unusual engine responses which may be the result of a particular engine in a given cell environment. To be specific, turbojet engines tend to oscillate slightly even after having been stabilized at a given power setting. Cyclic variations in fuel flow, turbine temperatures, and inlet pressures may result in a slight oscillation in engine RPM and thrust. A stable engine may not vary more than 10 to 20 RPM at a maximum of 8,000 RPM. This amount would not be serious or measurable.

The influence of a cell on engine oscillation may be illustrated by considering the ejector tube pumping action within the cell. As more secondary air is being pumped into the augmenter tube by way of a slight increase in exhaust gas velocity, the cell room will experience a slight pressure drop. The pressure drop causes a mass flow reduction through the engine. This reduced mass flow, in turn, reduces the ejector pumping action. With the pumping action reduced, the cell room pressure rises. This slight increase in pressure causes an increase at the engine inlet and the cycle begins again. In some instances, this can build in amplitude, making it difficult to obtain correct RPM and thrust measurements.

One of the contributive causes of this oscillatory condition is inadequate engine room cross sectional area. When the engine room is narrow, the secondary airflow passing the engine to the augmenter is more responsive to the pumping action of the augmenter system. If serious oscillations occur in a cell of small cross-sectional area, the most obvious method of correcting the deficiency is to provide an additional source for secondary air. The additional source may be an inlet duct near the augmenter tube inlet. To avoid undue cell room turbulence caused by an improperly placed secondary air intake, scale model flow studies should be made.

5. Need for Monitoring

The test engineer should make a study of the velocity distribution in the airflow path between the cell intake area and the engine bellmouth.

The pressure distribution should be defined and monitored frequently with adequate instrumentation to assure proper flow conditions. Where more severe problems arise, additional monitoring instrumentation may be necessary to provide complete evaluation data. If the pressure distribution problem becomes acute, as might result from testing larger engines, modification to the test cell will be necessary.

Instrumentation required for the evaluation and analysis of the pressure distribution is discussed in Section VI.

C. Temperature Distribution

The temperature distribution at the engine inlet has less effect upon engine operating performance than pressure. Nevertheless, it is recommended that temperature differences laterally across the inlet be as small as possible. Recirculation of exhaust gases are the primary cause of elevated temperatures at the engine inlet. Although significant in itself, recirculation is generally evidence of more serious problems with the ejector or exhaust treatment. Further cause for concern arises from the fact that excessive temperature at the bellmouth inlet will decrease the engine stall margin. This, of course, is dangerous to the operation of the turbojet as flameouts may occur whenever the engine is operated near its stall margin.

1. Heating Effects from Intake Turbulences

Certain cell configurations may cause an uneven temperature distribution at the engine inlet with effects similar to those experienced from uneven pressure distribution. An intake designed with unusual geometric configurations will create a turbulence by such flow disruption. Slight heating may occur at the inlet region of the bellmouth as a result of this turbulence and cause temperature differences in excess of $5^{o}F$. This can amount to at least a one-percent error in the calculation of the temperature correction factor θ. See Section III-B.

From a consideration of the temperature correction factor, " $\sqrt{\theta}$ " the influence which a temperature change will have on engine performance parameters can be seen. For a change in ambient or inlet temperature of $20^{o}F$, (i.e., from $T_{a_1} = 529^{o}$ Rankine to $T_{a_2} = 509^{o}$ Rankine), the correction factor changes approximately 2 percent.

2. Representative Average Temperature

An even temperature distribution of the engine compressor inlet is required for ideal testing conditions. Slight variations are normal and are compensated for in engine performance corrections by the use of an average inlet temperature. To determine a representative average, a minimum of four temperature measuring positions should be provided at the centers of the flow quadrant areas of the inlet. The average temperature of these four positions should normally be within the accuracies of the other parameter measurements. Some cases, such as checking for recirculation, may require temperature measurements at four additional positions. In fact, a general temperature increase at the compressor inlet will be the first indication of a recirculatory condition. Temperature measurement, then, can furnish a needed warning device to provide safe engine operation.

3. External Cell Recirculation

Two forms of exhaust gas recirculation exist. One is the recirculation which occurs within the cell, sometimes within the engine room. The other is that which returns through the intake systems from the exit of the exhaust stack treatment.

Recirculation may be caused externally by strong winds blowing across the exhaust stack toward the intake duct opening and, except in the early planning stage, is almost unavoidable. It is frequently necessary to discontinue testing when such recirculation occurs. Precautions should be taken prior to cell orientation planning to assure that prevailing winds will cause the hot exhaust gases to be carried away from the cell proper and especially away from the intake openings. A meteorological study is of great value at the planning stage.

External recirculation can be eliminated or minimized by proper cell design layout. Maximum vertical and horizontal separation should be obtained between the exhaust stack and intake openings.

4. Internal Cell Recirculation

Exhaust gas recirculation within the cell should be controlled by proper design of the augmenter and proper construction of the augmenter and the walls between the engine room and the exhaust chambers. The proper design of augmenter tubes is discussed in Section V-C and is summarized in Appendix C. An augmenter tube which pumps too much secondary air into the exhaust system may cause a buildup of pressure at (1) the cooling crosses or rings, or (2) the diffuser. This pressure buildup may cause flow to return forward along the walls of the augmenter through the cell to the engine inlet position. Back pressure, as such, is discussed in the next Section.

All exhaust gas leaks from the exhaust plenum to the engine room must be eliminated. Leaks may occur where water pipes pass through walls or where the augmenter tube is bolted to the wall. Poor seals around the doors and between the wall sections may allow exhaust gases to return to the engine inlet. Design and construction should be such that all possibilities of exhaust gases returning to the engine room are eliminated.

D. Back Pressure

A small amount of back pressure within the augmenter tube may be allowed if no recirculation occurs. Back pressure may exist if there are obstructions to the flow downstream from the exhaust nozzle. Some of the obstructions which may be found in the exhaust system are (1) water cooling crosses, posts, or rings, (2) diffuser networks, (3) acoustic treatment, and (4) turning vanes. All of these impose flow restrictions on the hot gas. Bends, if they cause excessive turbulence, may also contribute to a buildup of back pressure. For bends of 45 degrees or greater, it is usually advisable to use turning vanes. See Figure 2.

When results of back pressure are observed (either hot gas recirculation or an increase in tailpipe temperature), modification or repair to the exhaust system is necessary. An evaluation should be made from airflow and temperature measurements within the exhaust system. An analysis of the system may indicate a need for one or more of the following five modifications:

a. The augmenter or ejector should be modified to provide less pumping of secondary air, or the diffuser should be altered to allow a greater volume of air to pass. A reduction in the augmenter pumping efficiency, causing a reduction in the flow of secondary air, can be accomplished by lowering the length/diameter ratio. See Figure 28 in Appendix C. An increase in the opening area of the diffuser will reduce the diffuser flow resistance and hence allow a greater volume flow of gas.

b. A cooling system which is exposed to the flow within the augmenter may be redesigned to place a smaller restriction upon the flow. For example, a cross-shaped water discharger might be replaced by a conical shape which permits greater airflow past it.

c. The flow area through the diffuser system may be increased. The ring or angle iron on which the diffuser is mounted sometimes presents flow restriction. Such beams could possibly be notched to provide sufficient flow area. Even small amounts of additional flow area can alleviate back pressure. Another possible solution is to increase the flow area through the diffuser element plate. Increases of two to five percent, in some instances, may be all that is required to correct a back pressure difficulty. The static pressure at positions along the inner wall of a typical augmenter are plotted against augmenter stations for several augmenter terminal conditions in Figure 17.

d. The exhaust treatment open area can be increased. Back pressure may be caused when too small a flow area is allowed through the silencing treatment. If the flow is required to compress to a small flow area after expanding from the diffuser, the velocity is increased accordingly. Back pressure is then exerted and may even be observed at the inlet to the augmenter tube.

e. The pressure recovery of the exhaust system may be improved. Good pressure recovery diffusers can be added to the augmenter tube or to the exhaust treatment. Back pressure at the engine will be reduced as the pressure recovery is increased.

Pressure recovery can be obtained by providing a gradual expansion of the flow. Truncated conical duct sections expanding downstream can be placed at the end of the augmenter tube and expanding bellmouth ducts can be installed at the exit of the exhaust treatment.

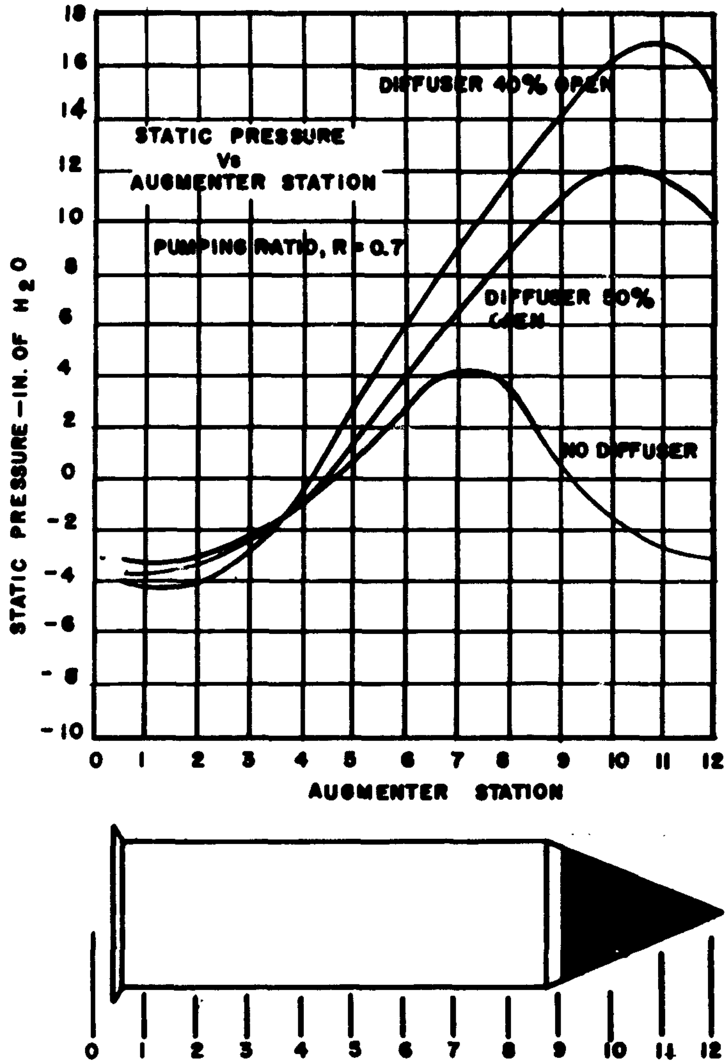


Figure 17. Static Pressure Variations Within a Typical Augmenter

E. Water Cooling of Exhaust Flow

Water cooling is normally utilized during turbojet afterburner operation in test cells and ground run-up noise suppression facilities. These facilities may be permanent, semi-portable, or portable. By introducing water in the form of a spray into the mixing section of the augmenter, the exhaust gas temperature is sufficiently reduced by the latent heat of evaporation to permit the use of basic acoustic treatment.

1. Cooling for Treatment Conservation

Noise suppression systems have a longer life expectancy when water cooling is used. The amount of water is determined from the temperature limitation of the final gas and water-vapor mixture. The temperature capabilities of the materials used in the exhaust system determine the maximum allowable temperature.

When stainless steels and high-temperature metals are used in the exhaust system, the mixed gas temperature may be as high as 900°F. However, a heat resistant material should be used for the acoustic insulation. Basaltwool, for instance, can withstand continuous temperatures as high as 1400°F. Stainless steels are generally used for turning vanes and cooling rings where only small amounts of water are available.

When diffusers are used in the augmenter tube, the water spray system should be located far enough forward of the diffuser to permit sufficient cooling of the hot gas flow before it reaches the diffuser material.

2. Aerodynamic Relationships

The amount of water required for cooling is also a function of the pumping ratio experienced in the augmenter tube. The more pumping permissible, the less cooling water required. Normally, the pumping ratio should be established first. The amount of water required to obtain the allowable mixed gas temperature should then be determined. Equations for the determination of the volume of water required in relation to secondary air pumping are presented in Appendix D. A typical design selection is presented in Section V-F-2-a.

For an established design, it may be desirable to reduce the exhaust velocity through the acoustic treatment by using water. Essentially, additional cooling water will lower the mixed gas temperature. A lower temperature has the effect of reducing the volume flow and, consequently, lowers the velocity. Water cooling in cell design is discussed in Section V-3.

The use of cooling water in existing cells is one method that can be used to correct excessive exhaust stack velocity problems or excessive treatment wear problems. Of course, additional water cooling will not correct major cell design deficiencies. Extreme cases of high exhaust stack velocities will require general increases in flow area.

SECTION V

CELL DESIGN CRITERIA

An optimum engine test cell design requires proper balance of the acoustic, aerodynamic, and thermodynamic characteristics. Design considerations should minimize cell reverberation.

Turbulent airflow should be avoided both for reasons of safety and for engine test environment considerations. Proper augmenter pumping should provide sufficient air for cooling the exhaust gases to a degree which will result in long service life of the cell exhaust treatment. Cooling water, turning vanes, diffusers, and multiple bend treatments should not adversely influence performance. The following Section describes ideal cell operating conditions and allowable variation of those conditions.

A. Cell Reverberation

Mention should be made at this point of the possible existence of noise levels within the test cell that would be detrimental to engine performance and personnel well-being. Excessive sound pressure levels can cause malfunctioning in both the instrumentation transducers which measure engine performance and some mechanical parts of the engine. In addition, structural vibration excited by sound pressure waves may occur in both the engine and the associated equipment within the engine room. The possibility of structural and equipment deformation or damage increases as engines which produce higher acoustic power levels are tested.

Noise induced vibration may be improperly interpreted as engine malfunction. Excitations registered by the engine vibration pickup can result from external as well as internal sources. Therefore, noise levels within the cell must be reduced as much as possible to help establish only that vibration caused by internal engine sources.

Proper acoustic design depends on several cell conditions. First, the augmenter tube should contain no protuberances or obstructions that will reflect noise back into the engine room.

The walls of the engine room should be covered with absorptive material to reduce the reverberant field in the cell as much as possible. Proper placement of the augmenter in relation to the engine nozzle can reduce the noise radiated back into the engine room from the positions where aerodynamic noise is generated.

An engine nozzle is usually inserted 6 to 24 inches into the inlet of the augmenter for portable ground run-up suppressor operation. The augmenter opening for this type of suppressor is designed to provide a 6 to 12 inch clearance around the nozzle. Clearance must be sufficient to permit adequate pumping of secondary air without influencing the tailpipe temperature and pressure. On the other hand, clearance must be held to a minimum to reduce the angle of noise radiation from the opening.

B. Cell Airflow

1. Intake System

Gas flow can characteristically be described by the continuity relation which presents the interdependence of the mass flow (m), velocity (V), density (ρ), and cross sectional area (A) of the flow channel. Presented here:

$$m = \rho AV$$

The design of the intake treatment then involves consideration of all factors which effect the relation above in addition to the basic acoustic treatment requirements.

It is necessary, therefore, to establish the mass flow requirement into the cell prior to the final acoustic design. Specific airflow requirements may be determined through a summation of the primary and secondary air demands and an allowance for future expansion of the system, where advisable.

Next it is desirable to establish the maximum acceptable cell depression limit.

Finally, with the mass flow requirements established and the cell depression fixed only the cross sectional area and flow velocity are variable, and their interdependence establishes the limits of economical design.

High intake velocities are undesirable from the standpoint of the erosion effects on acoustic treatment, ram pressure effects on the engine and resultant high duct losses (cell depression). On the other hand, large intake openings may require excessive amounts of acoustic treatment and, obviously, large superstructures.

Each of the above factors contributes to the final compromise between size, shape, economics and adequacy.

The acoustic treatment may consist of parallel baffles or lined ducts and lined bends. The treatment usually consists of perforated plates covering formboard or a fibrous matting. The attenuating material may range from 1 to 8 inches thick, depending on the amount and character of the noise reduction desired. Even 12-inch thick panels have been used where attenuation was desired in the low frequency range.

For most types of conventional intake systems, a design velocity of some 30 to 60 ft/sec. is recommended. Typical cell depression for a velocity of 50 ft/sec. through an intake with two lined bends is 2.2 inches of water.

To illustrate a typical design problem, the following example is presented:

<u>Example 1:</u>

<u>Problem:</u> Find the required intake stack open area for a test cell whose cell depression (Δp) cannot exceed 8 inches of H_2O. Two right angle bends are permissible. The outside air temperature is 70^oF.

<u>Assume the following engine operating conditions:</u>

Primary mass flow, W_p,	=	270 lb/sec
Primary exhaust temperature, t_p	=	1000^oF
Pumping ratio, R	=	1.0
Ambient temperature of air, t_a	=	70^oF
or T_a	=	529^o Rankine

<u>Procedure:</u> First, assume that 0.68 in/H_2O pressure drop will result from each 90^o bend. See Figure 20. With two bends a remainder of 6.67 inches of water (8.0 - 1.33 = 6.67) will be available solely for a velocity type pressure drop. Using equation IV-1 velocity can be found from

$$v_1 = \left[\frac{\Delta p T_a}{0.173}\right]^{1/2} = \left[\frac{6.67 \times 529}{0.173}\right]^{1/2} = 143 \text{ ft/sec}$$

Second, a pumping ratio of 1.0 indicates that primary air plus secondary air will result in a total of 540 lb/sec. mass flow through the intake system. At an ambient temperature of 70°F this volume flow will be

$$V_1 = \frac{540\ \text{lb/sec}}{.076\ \text{lb/ft}^3}$$

or

$$V_1 = 7100\ \text{ft}^3\text{/sec}$$

Third, the flow cross-sectional area through the intake treatment is found by

$$A_o = \frac{V_1}{v_1} = \frac{7100\ \text{ft}^3\text{/sec}}{143\ \text{ft/sec}}$$

or

$$A_o = 49.5\ \text{ft}^2$$

From this it can be seen that the open area of this intake treatment should be approximately 50 square feet.

Further consideration of this intake velocity indicates that a sturdy, more expensive acoustic treatment would have to be installed in order to withstand the high velocity flow. Typical sound treatments which would satisfy the flow area requirements are shown in Figure 18. A lined duct and a parallel baffle treatment with approximate opening of 50 square feet flow area, are shown as treatments A and B.

Treatment C of Figure 18 illustrates a cross-sectional area of 125 ft². Operating the above engine in a cell with this intake treatment would result in an intake velocity of

$$v_1 = \frac{V_1}{A_o} = \frac{7100\ \text{ft}^3\text{/sec}}{125\ \text{ft}^2} \quad \text{(from Eq. IV-3)}$$

or

$$v_1 = 57\ \text{ft/sec}$$

Then the cell depression, p_{vel}, (due to the velocity effect) would be

$$\Delta p_{vel} = 0.173\,\frac{v^2}{T_a} = \frac{(0.173)(3249)}{529}$$

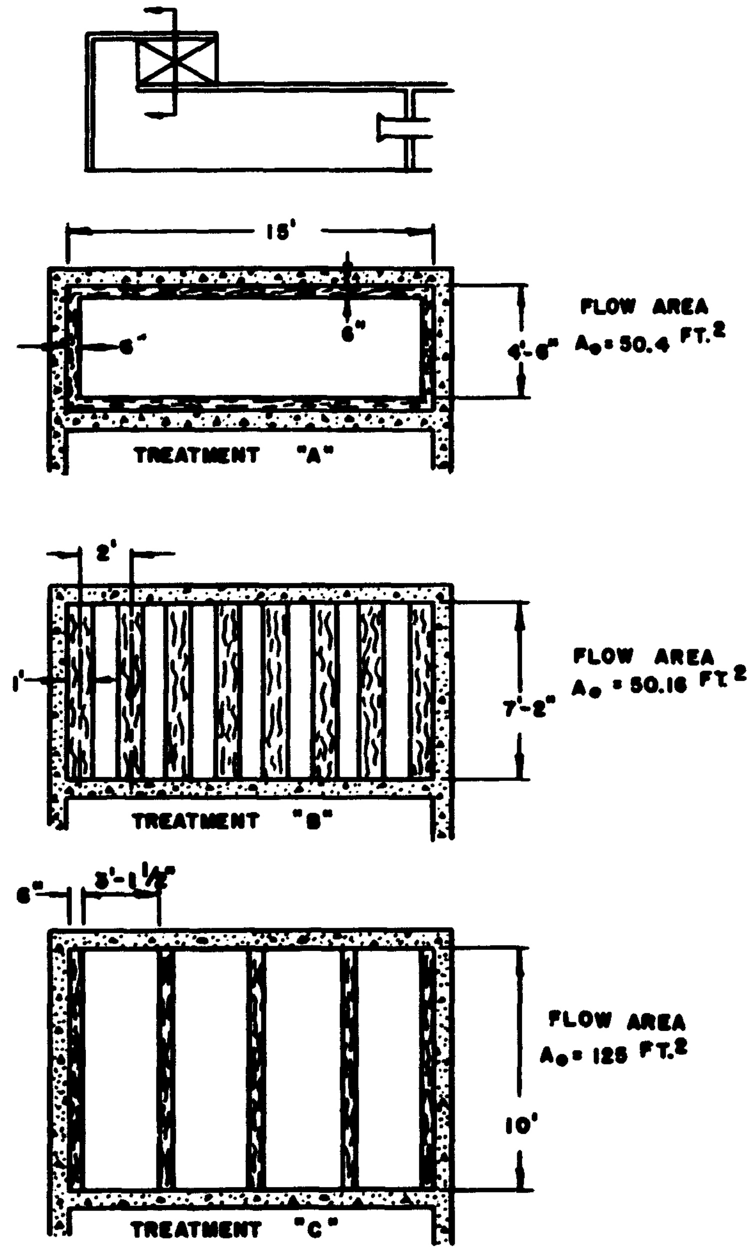


Figure 18. Some Suggested Intake Treatments

or

$$\Delta p_{vel} = 1.06 \text{ in. of water}$$

However, the total cell depression would include the effect of two 90° bends, or

$$\Delta p_{total} = \Delta p_{vel} + \Delta p_{bends}$$

$$\Delta p_{total} = (1.06) + (1.33)$$

and

$$\Delta p_{total} = 2.4 \text{ in. of water}$$

The cell depression, here, would be well within specification requirements.

2. Cell Room

In designing the engine room it is necessary to maintain certain physical relationships between the engine and the walls and ceiling and between the engine bellmouth and the intake treatment duct opening. The cross-sectional area of the engine room should be large enough to maintain the air velocity at a minimum.

The velocity of the secondary air as it passes between the engine and the cell walls, ceiling, and floor should average less than 20 ft/sec.

The following examples for 270-lb/sec engine operation (ref: Example 1, Page 36), will be used to show the difference between an acceptable design cross-section and a poor design cross section.

Example 2:

Problem: Determine the cell room velocity for a cell where height and width dimensions are 19 ft and 15 ft respectively, using the same engine described in Example 1.

Assumptions: See Example 1.

Procedure: The total cross-sectional area through which the incoming primary and secondary air would have to flow would be 285 sq ft. Considering that the bellmouth inlet of the engine is approximately 19 sq ft, then the cross-sectional area past the engine is approximately 266 sq ft. With an incoming volume flow of 7100 cu ft/sec, the velocity immediately in front of the bellmouth is 26.7 ft/sec. Considering a pumping ratio of 1.0, the velocity alongside the engine is approximately 13 ft/sec, which is well within acceptable values.

Example 3:

Problem: Determine the cell room velocities for a cell whose height and width dimensions are 12 ft and 12 ft respectively, using the same engine described in Example 1.

Assumptions: See Example 1.

Procedure: If the cell dimensions were reduced to 12 ft by 12 ft, the cross-sectional area in front of the engine position would be 144 sq ft. This leaves a cross-sectional area of approximately 125 sq ft between the engine and the walls. Calculation shows velocities of 56.8 ft/sec in front of the engine and 28.4 ft/sec alongside the engine.

As discussed in Section III-B, a ram pressure correction factor must be applied to the measured engine thrust when the velocity through the cell is excessive. Solving Equation (III-2) for the cross-sectional area of the engine room, A_t, yields the following:

$$A_t = \frac{\left(\frac{W_p \sqrt{\theta}}{\delta} \right)^2}{K \left(\frac{F_g}{\delta} \right)} \qquad \text{(V-1)}$$

The evaluation process should begin with the selection of a ram pressure correction factor, $\mathcal{N}$, and a desired augmenter pumping ratio, R. A value of $\mathcal{N}$ should be chosen in the 1.005 to 1.025 range. Values beyond these limits will either be impractical or result in too great a cell room velocity. A practical value of the pumping ratio, R, is 1.0. A corresponding value for K may then be calculated from Equation (III-1). (Figure 10 shows $\mathcal{N}$ versus K for three values of R). Cell cross-sectional area may then be determined from the above equation.

The following example illustrates how to determine the minimum cross-sectional area of the engine room and the consequent velocities in the engine room.

Example 4:

Problem: Find the cell room cross-sectional area and resultant velocity for a selected $\mathcal{N}$ and R, using the 270-lb/sec engine described in Example 1.

Assumptions: See as Example 1.

Procedure: Select a permissible ram pressure correction factor of 1.015. Referring to the graph of Figure 10, the curve for the assumed pumping ratio of 1.0 shows K equal to 0.0246. With the assumed engine weight-flow and thrust the cell cross-sectional area in front of the engine may be calculated from Equation (V-1) above.

$$A_t = 198 \text{ ft}^2$$

The intake volume flow as previously calculated for the 270-lb/sec engine at a pumping ratio of 1.0 is 7100 cu ft/sec. Thus, the velocity in front of the engine equals the volume flow divided by

A_t, or 35.9 ft/sec. Assuming that the engine has a frontal area of 19 sq ft, the open cross-sectional area between the engine and the walls is 179 sq ft. The velocity beside the engine equals the volume flow of the secondary air only, divided by the open area. Thus, the velocity is equal to (3550)/(179), or 19.8 ft/sec for this condition, or,

$$v_{cell} = 20 \text{ ft/sec}$$

The importance of selecting a realistic ram-pressure correction factor is illustrated in Examples 5 and 6. Note the increase in cell cross-sectional areas and resultant decrease in velocity when $\mathcal{N}$ (hence also, K) is reduced.

Example 5:

Problem: Find the required cell room cross-sectional area and velocity for a $\mathcal{N}$ value of 1.010, using the same engine described in Example 1.

Assumptions: Same as for Example 1.

Procedure: The ram pressure correction factor selected is 1.010. From the graph in Figure 10, K for a pumping ratio of 1.0 is 0.0164. Calculating A_t as before, the value of the cross-sectional area is 296 sq ft. Such a cross-sectional area results in a secondary air flow velocity past the sides of the engine of 12.8 ft/sec.

$$A_t = 296 \text{ ft}^2$$

$$v_{cell} = 13 \text{ ft/sec}$$

Example 6:

Problem: Find the required cross-sectional area and velocity for a $\mathcal{N}$ value of 1.005, using the same engine described in Example 1.

Assumptions: Same as Example 1.

Procedure: If the correction factor is reduced further, such as would result from only 0.5 percent change in thrust, the ram pressure correction would be 1.005. From Figure 10, with a pumping ratio of 1.0, the K factor becomes 0.0082. Thus, the cross-sectional area of the cell, A_t, equals 592 sq ft. This could be met with wall and ceiling dimensions of 20 ft. by 29.6 ft, respectively. The velocity of the secondary air as it passes the sides of the engine is reduced to a mere 6.2 ft/sec, less than one-fourth that of the original example.

$$A_t = 592 \text{ ft}^2$$

$$v_{cell} = 6 \text{ ft/sec}$$

It should also be pointed out that when secondary air pumping ratio is between 0 and 0.4 and engine-room air velocities are low simultaneously, there is danger of internal recirculation. An augmenter design that provides a pumping ratio greater than 1.0 will, in most cases preclude the possibility of recirculation.

It should be noted that the design of the cell room is closely associated with the intake treatment design. These sections should be considered together during the design phase.

3. Augmenter-Diffuser Design

The augmenter pumps cool air, promotes mixing of the hot exhaust gas and the cool air, and conducts the hot exhaust gases away from the engine room. Thus preparations are made for ejecting the gases through noise reduction components.

Frequently a diffuser is used in association with the augmenter. The diffuser is, essentially, a device that breaks up the exhaust flow into a large number of smaller jets. Noise generated by a hot gas nozzle is a function of the physical size and shape of the nozzle, the flow velocity, and the turbulence generated at the gas flow-still-air interface.

It must be noted that the open area of the diffuser through which the hot gases flow (the combined area of the small nozzles or holes) must be equal to or greater than the cross-sectional area of the augmenter tube. If this is not so, sufficient static pressure may be established within the augmenter tube to result in recirculation of gas out the front of the augmenter.

Pumping of too much secondary air can be detrimental to good engine testing. Aside from the fact that high velocities through the cell room may cause vibration of equipment located near the engine, the resultant drag against the engine may cause errors in the indication of thrust as discussed in Section III. The optimum pumping ratio for these considerations lies between 1.0 and 2.0. Of course this is dependent upon the augmenter tube diameter in relation to the nozzle diameter. The secondary air velocity through the augmenter inlet should not be in excess of 300 ft/sec. If the static pressure is reduced in magnitude so that the difference between the cell room pressure and the augmenter tube pressure attains the order of 30 in. of water, the shearing forces acting on the nozzle will begin to influence the thrust measurements. This condition applies to closely coupled (nozzle to augmenter) systems. Naturally if the engine nozzle is a distance of two or three nozzle diameters in front of the augmenter, the augmenter inlet velocities will have much less or no influence on the nozzle conditions.

The use of diffusers in conjunction with augmentation systems is widespread. However, caution must be used in their design to assure unobstructed flow through the ejector. Flow area through the screens or perforated plates of the diffuser should be in the range of 30 percent to 40 percent open for best flow conditions. When the flow area exceeds 40 percent open, the diffuser action becomes less effective and less noise reduction at the low frequencies will result. However, the flow area through the screen or perforated plate of the diffuser must be greater than the cross-sectional area of the flow into the diffuser or serious restrictions to the flow are imposed upon the augmenter system and back pressure may result. Flow areas of approximately 30 percent are recommended, depending on shape, but 10 percent per area have been employed quite effectively.

It should be noted that the foregoing discussion concerning the open areas of the screens and plates refers to the diffuser shapes shown in Figure 19.

For most diffusers a good rule-of-thumb is to allow a total open area through the diffuser of from 1-1/2 to 2 times the cross-sectional area of the augmenter tube.

Other types of diffusers have been used with varying degrees of success. One type, of moderate success, places many bars or rods such that they protrude radially into the exhaust flow from the walls of the augmenter. Caution must be used in every system to insure that the flow area at any one position is not reduced significantly. Sometimes it may be necessary to determine the ideal blockage area of a new diffuser by model studies or in-the-cell evaluations

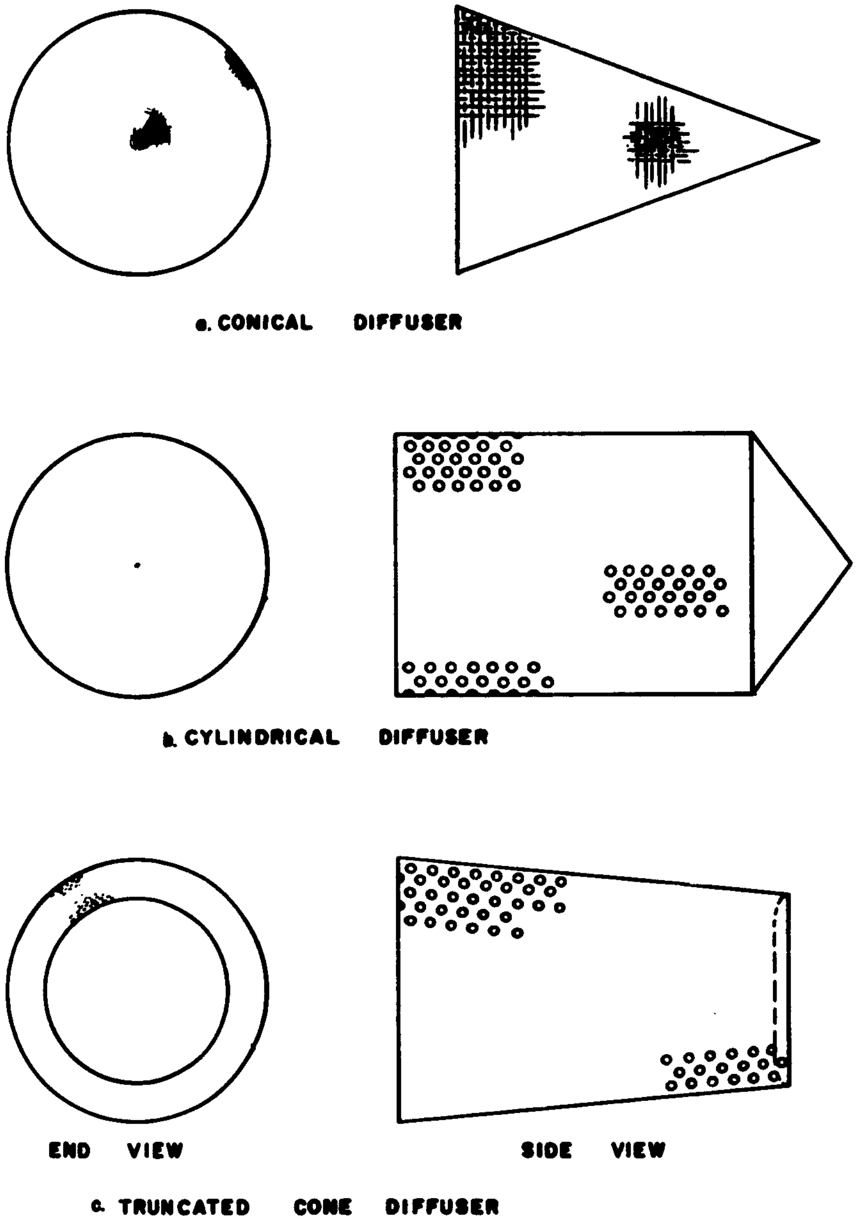


Figure 19. Typical Diffuser Shapes

Since the diffuser, in effect, distributes the gas flow from a central core or stream to a much wider flow area this expansion is enhanced when the flow is dumped into a large cavity or chamber. In permanent cell installations this chamber can be quite large and will react acoustically similar to a plenum chamber. (These will be discussed in the next section.) However, in portable suppressors the effect of this expansion may be more subtle. In most cases the expansion for portables from the augmenter cross-sectional area to the horizontal suppressor body section will be limited to, at most, 1 to 5. Typical configurations for portables are shown in Figure 20. Note the expanding areas in the vicinity of the diffusers.

In order to maintain a pumping ratio of between 1.0 and 2.0, the range best suited to engine testing, the length-to-diameter (L/D) ratio of the augmenter tube should be approximately 2.0. The diameter of the augmenter should be, for economy of construction, not greater than three times the nozzle diameter of the largest engine to be used. The augmenter to nozzle area ratio normally should be below 7 or 8. With a greater area ratio the L/D required for proper pumping makes the total length of the augmenter tube prohibitive. Augmenter geometry as related to aerodynamic flow is discussed in Appendix C.

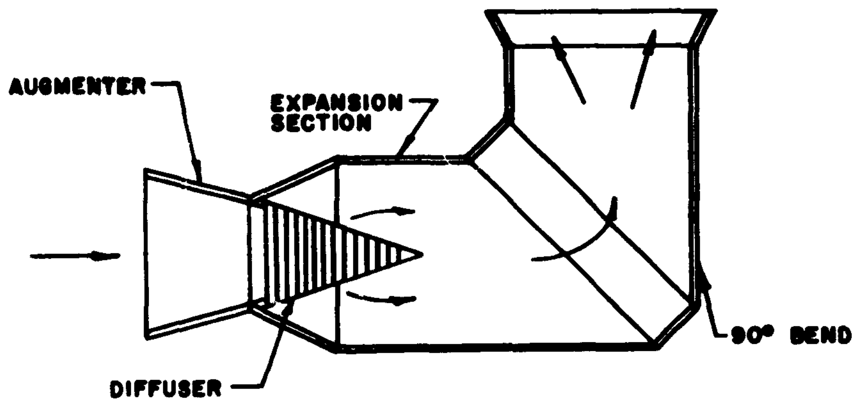
Placement of the diffuser in relation to the augmenter input is, of course, dependent upon the length required for the augmenter tube. The diffuser is usually mounted to the downstream end of the augmenter. The water injection system is placed upstream of the diffuser to provide adequate protection for the diffuser and subsequent acoustic treatment during afterburning operation. For a single cross-type water sparger it is necessary to have at least one full L/D between the water cross and the diffuser to allow adequate water dispersion. The amount of water to be pumped through the system may be determined from the equations given in Appendix D. However, it is wise to use no more water than is necessary, but, on the other hand, too little water may allow high-velocity, high-temperature flow deterioration of the augmenter, the diffuser, and the exhaust system.

Large billowy clouds of steam emanating from the exhaust stack during afterburner operation are a strong indication that more cooling water is being furnished than is necessary. Over many hours of operation this can be expensive and does not proportionally contribute to the cooling of the mixed gas through the exhaust system. The amount of water required should be determined from the specified final mixed exhaust gas temperature environment allowed for fibrous treatment of the exhaust stack acoustic system as discussed later in this Section.

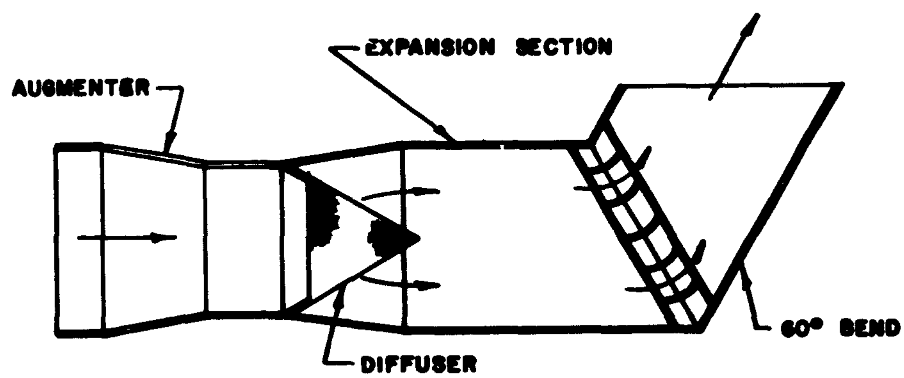
When designing for power of the largest engine to be placed within a cell, it is often economical to provide an adjustable water-supply pumping system. Otherwise, excessive water is pumped when the cell is used for small engines. Selection of a water pumping system and a water supply system should indeed be based upon the intended use of the cell.

Some of the major types of water spargers used in existing cells are described below:

a. The most widely used type of augmenter water cooling device is the spray ring. The spray ring is usually located at or near the augmenter inlet. Some multiple ring systems have a spacing of about one augmenter diameter between each of the rings. Water is injected into the exhaust gas stream from spray ejectors located on the inside, or toward the back side, of the ring, aimed at the center of the augmenter tube. A more refined spray ring system may incorporate the rings into the wall of the augmenter tube. Such a system presents no flow restriction or noise regeneration surfaces projecting into the augmenter tube.



TYPE "A"



TYPE "B"

Figure 20. Cutaway View of Typical Portable Turbojet Noise Suppressor

A system containing three or four water cooling rings, a capacity of 1,000 to 1,200 gal/min water flow, should be capable of handling most of today's large engines. However, this design usually precludes the use of a diffuser since it would be placed too far downstream of the engine nozzle to be acoustically effective.

b. Another widely used cooling sparger is the water cross. The water cross may be used separately or in conjunction with a ring. The water cross system ejects water on the downstream side of the pipe and depends upon the turbulence formed around the trailing edge of the pipe to diffuse the water into the hot gas stream.

The water cross sparger is not applicable to portable suppressor design because it becomes, by virtue of the high velocity stream flowing by it, a new noise source. To use the cross in test cells it may be necessary to reduce the noise level in the engine room by additional acoustic wall treatment.

Control of the water system is sometimes automatic, sometimes manual. Whenever the engine is throttled into afterburner setting, the water spray system should be activated. Ideally, the water spray system should be turned on a few seconds prior to afterburner ignition. However, some automatic systems utilize an increase in temperature in the augmenter or plenum to activate the on-valve at practically the instant afterburner ignition occurs.

One drawback in the use of water for cooling the exhaust gas flow is the need for an anti-freeze system in extremely cold climates. Electrical heating elements must be placed in jackets around all valves, switches, and pumps for such operation. Storage tanks must be drained immediately and filled within a short time interval before actual water cooling operation is to begin. For permanent test-cell water storage, underground tanks are an advantage for winterization.

4. Exhaust Treatment

Exhaust treatment systems have dual purposes: to conduct the mixed gas volume flow to external evacuation; and to provide a noise reduction path for the flow.

Good exhaust treatment design contains various methods for distributing the flow throughout the treatment. The use of a diffuser, as discussed in Section V-B-3, discusses the physical distribution of the gas flow. The use of turning vanes at bends in the system also helps. Some designs have included vertical vanes in the horizontal portion behind the augmenter. Figures 2 and 3 show a type of 90 degree turning vane that has been used successfully.

Exhaust stack and acoustic treatment design should provide for minimum flow velocities consistent with realistic sizing and economy of construction. Low exhaust stack velocities inhibit the formation of a new noise source (regeneration) at the exit of the exhaust stack. Normally, regeneration of noise can be avoided if the velocities through the treatment and out the exit are kept below 180 ft/sec. Also, in this regard, it is wise to consider the geometry of the exhaust stack acoustic treatment. Avoid the use of shapes that tend to increase turbulence at the exit. Cross braces, for instance, should be held to a minimum.

As mentioned previously, exhaust plenums are used in some cases where better noise reductions are required in the low-frequency range of the audible spectrum.

Cubical plenums are sometimes placed to the side of the central exhaust plenum. Some plenums are filled with acoustic splitter panels or wedge shape panels. These side plenums normally present no obstructions to the aerodynamic flow. However, turbulent eddies, inadvertently set up by improper placement of the plenums with respect to the augmenter outlet can cause excessive wear at localized positions in the treatment.

It is possible that plenums, in series with parallel baffles, can be used to good effect to increase noise reduction. When plenums are used this way the baffles should be designed so the open cross-sectional area increases from panel section to panel section as the flow progresses downstream toward the exit of the exhaust treatment.

Because normally high velocities (compared to intake system velocities) exist throughout the exhaust stack system, it is generally not advisable to design more than one bend into the exhaust treatment. However, one type of design with very high noise reduction capabilities uses lined ducts and multiple lined bends. This type of treatment (labyrinth) usually has an open area large enough that the velocities are kept low, i.e., in order of 100 to 150 ft/sec.

Figure 15 shows the typical velocities profile through a test cell which has been designed for a 270-lb/sec turbojet engine where a pumping ratio of 1.0 and a final temperature of 600°F have been assumed.

The desired average velocity through the exhaust stack system determines the construction of the sound absorption panels within the stack. Whether the path for the flow is serpentine or passes through straight parallel baffles, (See Figures 2 and 3) the velocity should not exceed 180 ft/sec for permanent cells, or 300 ft/sec for portable suppressors.

The following example illustrates a typical exhaust flow system.

Example 7:

Problem: Find the minimum open cross-sectional area of exhaust stack acoustic treatment and the minimum total exhaust stack cross-sectional area for a cell in which a J-75 will be operated with afterburner.

Assumptions:

J-75 turbojet engine		
Primary mass flow		W_p = 270-lb/sec
Primary exhaust temperature (afterburner)		t_p = 3150°F
Pumping ratio		R = 1.0
Ambient temperature/air		t_a = 70°F
	or	T_a = 529°Rankine
Final exhaust gas temperature		t_f = 600°F
Water for cooling		G.P.M. = 900 gal/min

Procedure: Using Equation (2) of Appendix D, the mixed gas temperature is 1740°F. With 900 GMP available the final exhaust gas temperature will be 600°F and the volume flow found, using Equation (7) of Appendix D, is 19,830 cu ft/sec.

From a basic rule that velocity times area equals volume flow, it may be seen that the open area through the exhaust treatment must be more than 110 sq ft in order to keep the velocity below 180 ft/sec.

$$A_o = \frac{V}{v} = \frac{19{,}830 \text{ cu ft/sec}}{180 \text{ ft/sec}}$$

$$A_o = 110 \text{ ft}^2$$

If there were no panels within the stack, the cross-sectional dimensions of the flow area (110 ft^2) of the exhaust stack could be, for instance, 10 ft by 11 ft. However, acoustic treatment occupies 50 percent to

60 percent of the exhaust stack cross-section. Then, assuming the acoustic treatment blocks 50 percent of the area, the total inside stack cross-sectional area would have to be twice 110 ft or a minimum of 220 sq ft. Inside cross-sectional dimensions of approximately 15 ft by 15 ft would satisfy the requirements.

The procedure used in the above example may be followed for all exhaust stack designs.

C. Cell Temperatures

1. Intake Treatment System

The intake treatment, for all practical purposes, is subjected to only the outside ambient temperature. Temperatures slightly lower than ambient that might occur are due to minor effects of expansion of air entering the cell (i.e., for polytropic expansion

$$T_2 = T_1 \left(P_2/P_1\right)^{\frac{n-1}{n}} \quad \text{since} \quad P_2/P_1 < 1 \quad \text{and } T_2 < T_1.)$$

The acoustic treatment used in the lining of the intake ducts and the baffles need only withstand a temperature range of -60°F to +120°F. Few temperature restrictions are placed upon the intake treatment and its design. Generally, inexpensive absorbing panels can be used effectively.

2. Engine Room

In the design of the cell room treatment and its associated equipment (as is true for the intake treatment), the temperature environment need not be considered to be in excess of the outside ambient temperatures. The temperature requirements of engine room hardware are, of course, the same as those for the intake system.

The engine nozzle-augmenter pumping action draws outside ambient air into the cell through the intake treatment. In some wind-tunnel engine testing the ambient air can be furnished from environmentally controlled reservoirs; however, this is too expensive for most testing facilities.

The turbojet engine itself generates heat within the cell. Heat given off by the engine is normally carried away with the secondary air into the augmenter tube. However, for brief periods when the engine is shut down and not yet cooled, much heat energy is radiated in the cell by the engine. At these times the temperature at the walls may exceed 100°F. For this reason the acoustic treatment of the walls should be selected to withstand a temperature as high as 130° to 140°F.

In instances, accidents such as tailcone fires during engine starts may occur and the walls of the engine room may be sprayed with burning fuel. Fire extinguishing systems activated automatically should be incorporated into all designs. Fire protection safety devices can reduce damage to the cell and to engine equipment and instrumentation. Accidents resulting from fire are rare, however. There are acoustic materials available that will not support combustion; it is advisable to use such materials on all engine room walls.

3. Augmenter-Diffuser System

Obviously the temperature environment of the augmenter-diffuser system increases drastically from that of the cell room. The augmenter conducts the hot gases away from the engine, dispensing them into the exhaust treatment system for expulsion. Normally the temperature at the bellmouth of the augmenter tube will not exceed the cell room temperature. This is true because of the large amounts of

secondary air flowing into the augmenter tube opening between the nozzle and the bellmouth. However, the hot gases and secondary air mix as they flow through the augmenter system and the temperature of the augmenter shell increases progressively downstream from the bellmouth. Generally, however, gas temperatures along the augmenter shell do not exceed 400°F prior to being ejected into the exhaust stack system. This condition would be true for military power operation. For afterburner this temperature would be kept below 400°F by virtue of the cooling water sprayed into the augmenter.

Differences, of course, exist between various systems. When diffusers are used at the termination of the augmenter tube, temperatures higher than 400°F may exist upstream from the diffuser along the shell of the augmenter tube. It is wise to design the augmenter-diffuser system so that the mixed gas temperature does not exceed 600°F to 800°F, even at the diffuser itself.

The mixed gas temperature as it emanates into the exhaust plenum below the exhaust stack treatment should average about 600°F for the typical example shown in Section V-F-1. During afterburner operation, water cooling must reduce the temperature from 3150°F at the nozzle to 600° to 800°F at the diffuser position.

There is no material at present suitable for use in an augmenter-diffuser system without water cooling during afterburner operation. The temperatures of the hot gas for military power, however, are sufficiently lowered by realistic amounts of secondary air pumping.

4. Exhaust Treatment

The temperature environment of the exhaust treatment system should be held to a minimum by the proper design of augmenter-diffuser system. Proper amounts of secondary air, and cooling water if necessary, should insure that the exhaust acoustic treatment is protected. The safe maximum temperature for normal use of fiberglass sound absorbing materials within parallel baffles of perforated plate is about 600°F. At temperatures in the range of 800°F, fiberglass begins to melt. Also as temperatures exceed 800°F, especially at velocities in the 150 to 180 ft/sec range, excessive panel deterioration is caused through oxidation, rust and deformation. This deformation is the high temperature warping of the steel plates of the panels due to temperature differential expansion of different pieces. When high temperature steel panels filled with steel wool rope are used, higher mixed exhaust gas temperatures are allowable. If stainless steel is used, temperatures of near 1000°F can be allowed within the exhaust stack system. Stainless steel is, of course, expensive and not usually considered economically feasible for use in the large quantities needed for an exhaust system.

When the temperature of the exhaust gases through the exhaust treatment exceeds the values mentioned above, the danger exists that metal particles may be ejected out the exhaust stack as flying sparks. Fires in the vicinity of the exhaust suppressor system have been caused in some instances.

5. Temperature - Conclusions

The temperature profile plotted in Figure 15(a) describes the approximate magnitudes of the environmental temperatures of the gas through the intake treatment, through the cell room, into the augmenter tube, through the diffuser, and out the exhaust treatment. The data shown are estimates for the example given in Section V-F (270-lb/sec mass flow engine). These are typical data for an adequately designed test cell.

D. Cell Pressures

The primary problems concerning changes in pressure throughout the cell are discussed in Part V-B. However, some further considerations should be given to the pressure variations that may occur within a test cell.

In general, pressure changes throughout the entire cell should never be abrupt. Maintaining gradual pressure changes is a vital part of providing a good test environment and air flow.

Variations in velocity profile will occur most frequently when the engine is not centered in the cell room, when the engine bellmouth is placed too close to the cell intake treatment, or when flow obstructions are found upstream from the bellmouth. Intake openings that are nonsymmetrical with respect to the engine inlet (see Figure 21) may cause excessive turbulence and should be avoided.

The walls used in construction of a jet engine test cell should be designed to withstand pressures of at least 150 lb/sq ft. For most test cell designs, steel-reinforced concrete walls are constructed to withstand differential pressures of 150 to 300 lb/sq ft, depending upon the particular cell requirement.

One reason for limiting cell depression is that the cell walls must withstand the forces placed upon them by the difference between ambient and interior pressure. However, pressures imposed on a cell wall due to cell depression are small. Note that a depression of 8 in. of water is a pressure differential of only 35 lb/sq ft (Figure 22). Such an amount seems insignificant when the walls might be designed to withstand a pressure as high as 150 lb/sq ft. In the exhaust stack however, where the pressure difference may be as high as 30 in. of water, the walls must withstand a pressure of 144 lb/sq ft. Such a differential pressure would still be safely below the pressure resistance capabilities of the walls.

The prime reason for careful consideration of high differential pressures is that, although infrequently, engines do explode. Tailcone fires are the usual cause for such explosions. Emergency explosion hatches are often provided in the ceiling section immediately above the engine test position. These hatches act as pressure release valves. They are designed to pop open under explosive pressures, thus relieving the pressure in the cell room before walls and equipment are damaged.

When multiple cells for use as aircraft enclosures are constructed side by side it is common practice that a given cell should not have more than one wall in common with another cell. This type of isolation is required to minimize the danger of an explosion occurring in one cell, causing subsequent explosions in the other cells.

While the pressure distribution throughout the cell is vitally important in cell design, it is also an integral part of velocity consideration. Figure 15(b) shows the plot of a typical pressure profile as the air flow passes through the cell from the intake to the exhaust exit. The values shown are typical estimates for a cell with a 270-lb/sec mass flow turbojet engine at military power.

E. Miscellaneous Considerations

Several miscellaneous considerations in cell design are: engine nozzle positioning in relation to the augmenter tube inlet; mechanical adjustment of the augmenter tube; special requirements of the portable suppressor augmenter tube where a slot is needed for close positioning; and placement of the observation window in relation to the jet engine.

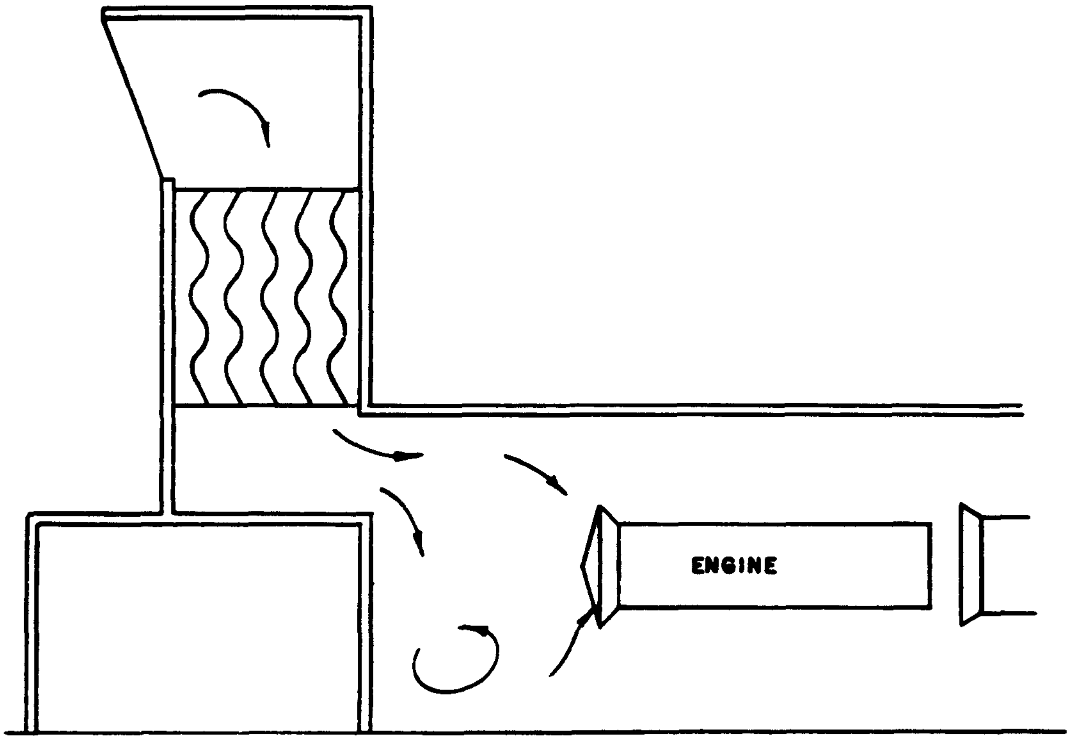


Figure 21. Nonsymmetrical Intake

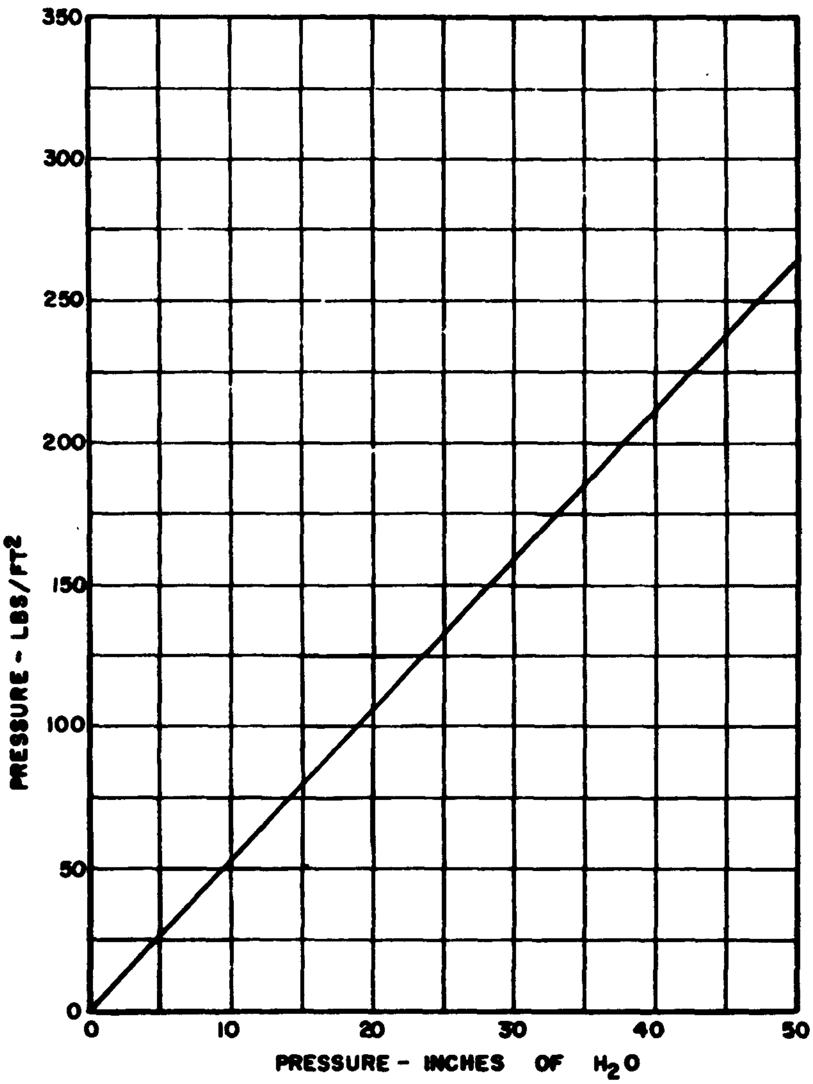


Figure 22. Pressure Conversion Chart - Inches of Water to Pounds per Square Foot (Temperature = 4° C)

1. Engine Nozzle Position

If the engine nozzle is placed too close to an augmenter tube, there is a possibility that the tailpipe temperature may be affected by the augmenter environment. Also, thrust measurements can be affected by excessive secondary air velocities and back pressures. On the other hand, if the nozzle is too far in front of the augmenter bellmouth, the amount of noise radiated into the cell will be increased. In general, for the closed test cell, the engine nozzle should not be more than one nozzle diameter in front of the augmenter tube. The amount of insertion of the nozzle into the augmenter for portable suppressors is dependent upon the size of the augmenter in relation to the nozzle. If adequate clearance all around the nozzle is maintained, insertion of as much as half a nozzle diameter may be possible. It is particularly advantageous to insert the nozzle into the augmenter tube a short distance for additional silencing with portable suppressors.

As the engine nozzle is brought close to the inlet of the augmenter, the volume flow of secondary air decreases somewhat by virtue of the decreased cross-sectional area between the nozzle and the inlet. The secondary air velocity does, however, experience an increase as the exhaust flow tries to maintain its pumping action.

One engine manufacturer* found the relationship between the distance from the nozzle to the augmenter inlet and the pumping ratio to be as shown in Figure 23. These data are for a nozzle size of approximately 2 ft (J65). It can be seen that the pumping ratio increased approximately 0.4 as the distance increased from zero to 5 ft.

It should be noted that for those operating conditions, the "rated speed thrust" changed 2.0 percent to 2.5 percent. See Figure 24. The influence of the secondary air pumping was more detrimental when the nozzle was close to the augmenter. This effect is primarily due to the increase in velocity of the secondary air entering the augmenter, causing a drag to be exerted upon the outside shell of the engine and nozzle. For this case (augmenter diameter of 5 ft) it was necessary that the nozzle-to-augmenter distance be not less than 4 ft.

2. Augmenter Adjustments

There are several mechanical methods for adjusting the augmenter position when an engine mount requires that the nozzle remain in a fixed position. First, there is the sliding type. An inner liner section of the augmenter tube usually telescopes forward to meet the engine nozzle. This section is mounted on legs with rollers and some means of locking the legs in place is provided. This type of augmenter arrangement is not too desirable. Since hot gases are ejected at high velocities out the aft end of the augmenter tube, the flow tends to seek a pressure escape to the lower pressure of the engine room through the space around the sliding augmenter tube. Recirculation may result.

The segmented type of augmenter adjustment has flanged insert sections available to mate with the different engines that are to be tested in the cell. These sections are bolted in place by means of heavy steel flanges. Proper structural bracing of the permanent section of the augmenter tube is required. In general, additional bracing is necessary when the length of the additional inserted sections exceeds the augmenter diameter.

For portable suppressors, the suppressor is brought to the engine. However, the mechanical tie-down of the aircraft or the engine test stand in relation to the tie-down of the suppressor makes it necessary to give some consideration to the

* Letter: J. P. Grandfield to 1/Lt. Elliott, 5 June, 1959, Wright Aeronautical Division, Curtiss-Wright Corp., Woodbridge, New Jersey

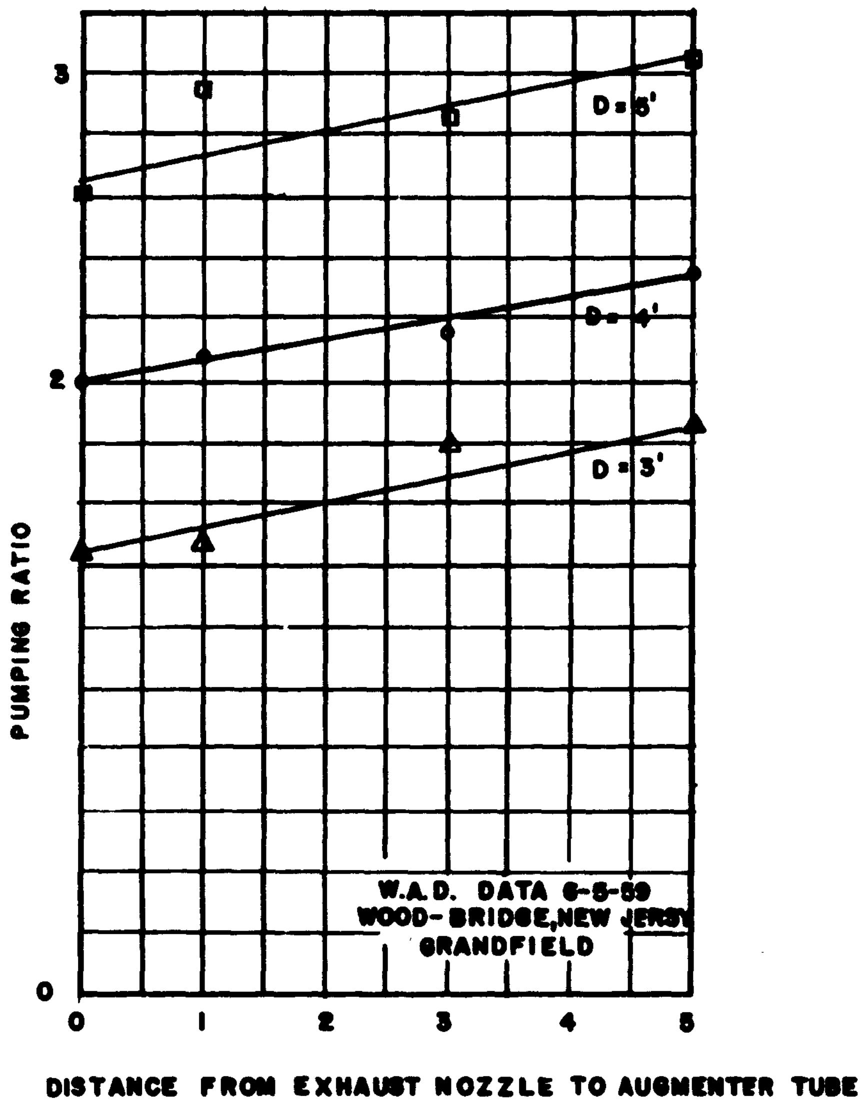


Figure 23. Pumping Ratio Versus Nozzle to Augmenter Distance

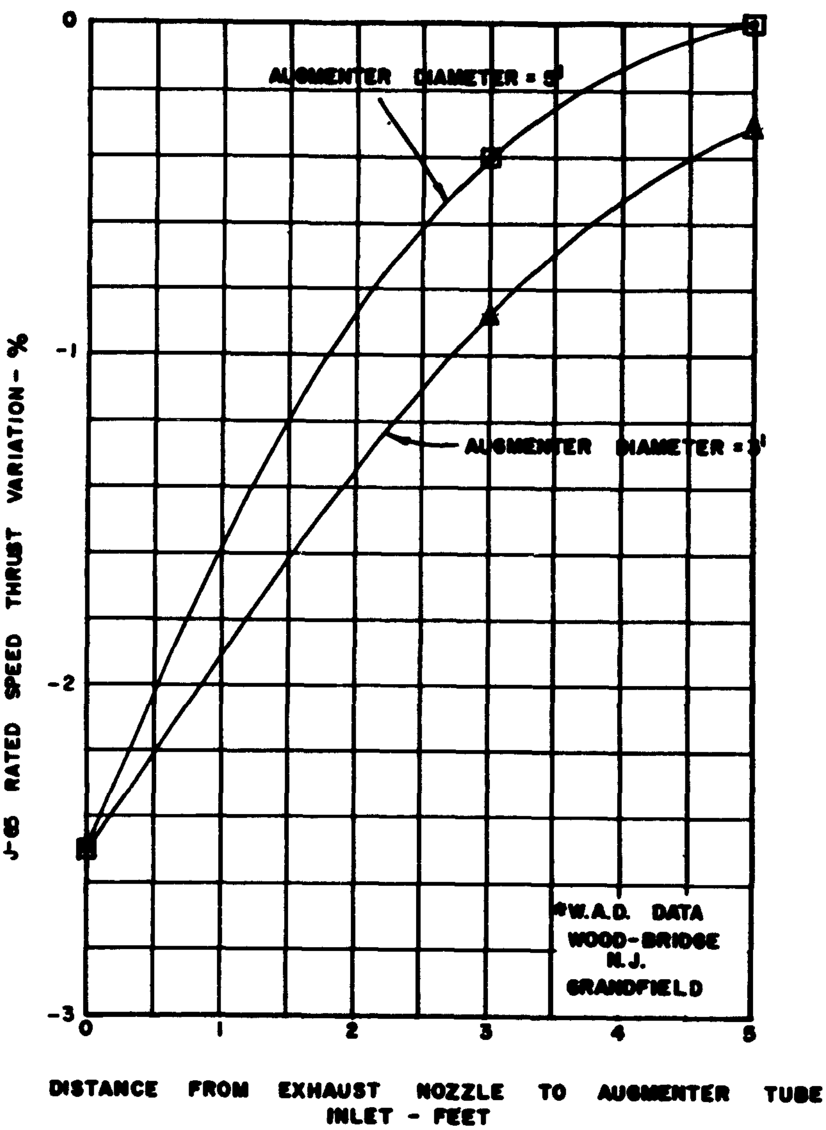


Figure 24. Speed Thrust Variation Versus Nozzle to Augmenter Distance

nozzle augmenter relationship. It is wise to use adjustable linkage between the suppressor and tie-down eyes, or between the suppressor and the legs of an engine dolly (or the struts of an aircraft). These adjustable tie-downs permit a final horizontal positioning of the suppressor.

3. Slotted Augmenter Tubes

Augmenter tubes with slots are primarily used for portable suppressors. They present several problems. The slot is provided to clear obstructions such as an aircraft tail or an engine-wing pylon.

The slotted augmenter tube must be treated somewhat differently than the straight augmenter tube. First, there is a static pressure reduction established at the forward end of the augmenter tube, caused by the pumping action of the jet nozzle. When the cylindrical shape of an augmenter is intact (no slot), the structure withstands this pressure differential with only a normal amount of bracing. However, thin-shelled or poorly braced augmenter tubes have collapsed inward at the front end under the high flow of military power operation. With a slot at the top or to the side, structural bracing of the augmenter tube inlet must be sufficient to withstand the high pressure differentials that build up at this point.

For representative static pressures at positions along the augmenter tube from the inlet to the diffuser see Figure 17. An increase in the magnitude of the pressure differential is seen as larger mass flow engines are used. The provision for structural reinforcement of the augmenter shell is vital for safety of operation of the engine and the suppressor or cell. The plots shown in Figure 17 were derived from model measurements using a jet engine simulator. The diameter of the augmenter was 15 inches and the length was 12 inches. The simulator nozzle diameter was 5 inches.

In the plot shown in Figure 17 the static pressure within the augmenter tube returns to ambient several feet in front of the diffuser section. For certain types of augmenter and diffuser designs in portable suppressors this change can occur close to the aft position of a slot. Obviously, if it occurs at the slot, the hot gas will be forced out of the augmenter at that point, endangering the aircraft, and could result in re-ingestion of the exhaust gas by the engine intake.

For a suppressor augmenter already constructed, the open area through the diffuser should be increased enough to reduce the pressure buildup in front of the diffuser. Second, the augmenter tube must be reduced in length to reduce the pumping efficiency. The longer the length of the augmenter tube, the more critical will be the required amount of opening through the diffuser. The slot length should be held to a minimum. Typical construction would set the augmenter tube L/D between 1-1/2 and 2, and the slot length less than 2/3 diameter for this particular type of portable suppressor.

4. Observation Window Location

Brief mention should be made of the logical positioning of an observation window or windows for a large test cell design. It is not wise to place the observation window in a direct radial line with the turbine rotor sections, since most internal failures result in turbine rotor blades being thrown through the shell of the engine. Thus, the observation window should be a little forward of the rotor sections.

F. Sample Design Problems

Applications of the foregoing discussions concerning aerodynamic and thermodynamic test cell design are to be illustrated here. Typical design problems are considered from the initial engine and cell specifications to the actual cell

sizing, and finally, to checkout operation in the final structure. From a knowledge of engine operating conditions and of restrictions to be imposed upon the cell, a procedure of arriving at the most acceptable aerodynamic and thermodynamic cell design is shown.

Engine operating conditions which must be known are:

a. Primary mass flow of the engine, W_p

b. Exhaust nozzle temperature, t_p

c. Ambient air temperature, T_c (The cell air temperature will be considered to be the same value as the ambient air temperature).

Specific requirements for the cell to be considered are:

a. Final mixed gas temperature (maximum to be allowed), t_m

b. Final volume flow of gas to be expended through the acoustic exhaust system, V_f. This restriction is usually considered in the form of a velocity maximum, v_f.

Operating restrictions that must be pre-set are:

a. Cell depression

b. Augmenter pumping ratio

c. Maximum mixed gas temperature

d. Maximum exhaust stack velocity

If afterburner operation is to be conducted, the designer must consider separately the special afterburner operating conditions. The same information must be known as with military operation, but due to the higher exhaust temperatures, which necessitate water cooling, the calculations are more complicated.

1. Typical Design Calculations for Military Power Operation

The engine will be considered at military power operation. Assumed operating conditions for this engine will be:

$$W_p = 270 \text{ lb/sec}$$

$$t_p = 1000^\circ F$$

$$t_m = 600^\circ F \text{ (or lower)}$$

$$t_c = 70^\circ F$$

a. Exhaust Stack Calculations. First, it will be necessary to select a pumping ratio, R, that will provide the desired mixed gas temperature. From Equation 8 (Appendix B) the exact pumping ratio may be calculated

$$R = 1.2 \quad \frac{t_p - t_m}{t_m - t_c} \qquad (V-2)$$

This value will become 0.905 when substituting the above operating conditions. Thus a pumping ratio of 1.0 may be chosen for these design calculations. A pumping ratio of 1.0 or greater will result in a mixed gas temperature below the required 600°F. Using R = 1.0, the mixed gas temperature may be found.

$$t_m = \frac{Rt_c + 1.2\ t_p}{R + 1.2}$$

or

$$t_m = 577^\circ F$$

The final volume flow V_f through the exhaust noise suppression system can be found from Equation 9 of Appendix D:

$$V_f = W_p\ (1 + R)\ (0.0253)\ (t_m + 459) \qquad \text{(V-3)}$$

Still assuming R equal to 1.0 and using the resulting T_m equal to 577°F, the final volume flow equals 14,150 cu ft/sec. In the selection of an acoustic treatment, a maximum allowable velocity through that treatment must be assumed. Normally, it is advisable that the velocity through the treatment not exceed 180 ft/sec. This is true for acoustic baffle panels stuffed with fiberglass or most fibrous materials. The combination of high velocity and high temperature is detrimental to the treatment and reduces its service life. With a set maximum velocity, the open flow area can be calculated. Volume flow being equal to velocity times area, the equation is:

$$A_f = V_f/v_{f\ max} \qquad \text{(V-4)}$$

For this example, A_f equals 14,150/180 which equals 78.5 sq ft. This should establish that the open paths through acoustic treatments in the exhaust system should not total less than 78.5 sq ft in cross-sectional area.

Considering that the exhaust stack cross-sectional area is 50 percent blocked by acoustic paneling, it can be determined that approximately twice the required flow area is necessary for the total cross-sectional area of the stack. For this example, then, the total inside cross-sectional area of the stack, using acoustic panels that block 50 percent of the area, should be 157 sq ft. In approximate dimensions, for instance, a stack 11 x 15 ft (inside) would meet the requirements for this military power operating condition.

To illustrate cell configuration differences that occur when other types of treatment are used, consider a treatment that utilizes 60 percent of the total cross-sectional area. As in the previous case, the required open area is considered 78.5 sq ft. With only 0.40 of the area being open, the total cross-sectional area for the treatment is 197 sq ft. This results in an increased wall width of one to two feet. Approximately 14 x 15 ft would probably be the inside dimension of the exhaust stack in which this acoustic treatment would be placed. These dimensions supply a cross-sectional area of 210 sq ft which indicates that approximately 11 percent more volume of concrete would have to be used in the stack walls.

b. Intake Calculations. The total intake flow into the cell room through the intake system must include both primary and secondary air. It can be determined from the equation

$$W_{in} = W_c + W_p = W_p\ (1 + R) \qquad \text{(V-5)}$$

As used for the exhaust calculations, W_p is equal to 270 lb/sec and R is assumed equal to 1.0. It follows, then that W_{in} is equal to 540 lb/sec. The intake volume flow may be calculated using the equation

$$V_{in} = \frac{W_{in}}{0.076} \qquad \text{(V-6)}$$

where 0.076 is the density of air in pounds per cubic foot. Thus, the intake volume flow is 7,100 cu ft/sec.

For intake treatments, it is wise to hold the velocity well below 100 ft/sec. The cross-sectional area through which the determined amount of intake volume flow will pass may be derived from the equation

$$A_{in} = V_{in}/v_{in\ max}$$

Using $v_{in\ max}$ equal to 60 ft/sec results in a flow area through the intake treatment of 118 sq ft.

Using a straight-lined duct for the intake treatment with 50 percent area utilization would result in an inside configuration of approximately 15 x 15 ft. If greater attenuation is needed, it could be supplied by a lined duct with a 90-degree bend; or, with parallel baffles. A typical parallel baffle design might have one third of the cross-sectional area blocked by parallel panels. Thus, the total stack inside cross-sectional area would be approximately 180 sq ft.

c. Augmenter Design Calculations. Limiting conditions determining the physical dimensions of the augmenter tube are: (1) engine mass flow, (2) engine nozzle diameter and (3) the pumping action required to provide cooling. Augmenter design is discussed later in Section F-3.

2. Typical Design Calculations for Afterburner Operation

When afterburner operation is required within the test cell, factors in addition to those presented for military operation must be considered. Thus, the following example is presented.

The assumed afterburner engine operating conditions will be:

$$W_p = 270 \text{ lb/sec}$$

$$t_p = 3{,}150^\circ F$$

A safe final mixed gas temperature should be:

$$t_f = 600^\circ F$$

A realistic selecting of a pumping ratio, R, would be

$$R = 1.0$$

a. Exhaust Stack Calculations. Using these conditions and assuming a cooling air temperature, t_c, equal to 70°F, it is necessary first to find the mixed gas temperature, t_m. As with the military power calculation, this temperature is found from Equation 2 of Appendix D. Using this equation, t_m equals 1,740°F.

It is then possible to calculate the amount of cooling water in gallons per minute required to assure a final temperature of 600°F. The amount may be found from Equation 4 of Appendix D:

$$GPM = W_p \ (1+R) \ \frac{.26(t_m - t_f)}{140 + 0.067t_f}$$

Using this equation, the amount of cooling water is 887 gal/min.

With the amount of cooling water known, the final volume flow resulting from these conditions can be found, using Equation 7 of Appendix D.

$$V_f = 0.0253 \ W_p \ (1+R)(t_f + 459) + 0.00563 \ GPM \ (t_f + 459) \qquad (V-7)$$

Evaluating this equation produces a final volume flow of 19,650 cu ft/sec.

The same velocity restrictions through acoustic panel treatments hold for afterburner operation. Thus, the total flow velocity can be calculated using Equation (V-4). In this example, the exhaust flow area is approximately 114 sq ft. If a 50 percent open treatment is considered for use in the exhaust stack, then the total inside cross-sectional area should be 228 sq ft. The inside dimensions of this stack could, for instance, be 23 x 10 ft, 20 x 11-1/2 ft, or 15 x 15 ft. If a treatment whose open area is 40 percent is used, the total cross-sectional area should be 285 sq ft. This treatment could be satisfied by stack dimensions of approximately 17 x 17 ft, or 15 x 19 ft. This results in approximately a 12 percent increase in the volume of concrete over that which is necessary for the 50 percent open treatment.

b. Intake Calculations. The design of the intake system for afterburner operation is the same as that for military power operation.

c. Augmenter Calculations. If the augmenter tube is designed for a pumping ratio of 1.0 at military power operation, it is usually true that afterburner operation will result in approximately the same or, perhaps, a smaller pumping ratio. Therefore, it is normal and even advantageous to design the augmenter tube for pumping ratios applicable for military power settings. Sample calculations are given in Section III.

3. Typical Augmenter Tube Calculations

Occasionally there are circumstances which place restrictions on the flow or the pumping ratio. At other times space available for the augmenter may be limited. To illustrate design considerations for these conditions and to show the results of variations in the length and diameter at various pumping ratios, the following examples are presented.

The following conditions will be assumed to exist at military power operation:

W_p = 270 lb/sec

T_p = 1000°F = 1459°Rankine

Engine Exhaust Mach Number = M_p = 1.0

T_c = 70°F = 529°Rankine

A pumping ratio of R equal to 1.0 is assumed as discussed in Section V-F-1.a. For this illustration, it may be assumed that the engine nozzle diameter is 2.5 ft. The exhaust nozzle area, A_p, is then $(6.25\pi)/4$.

It is first necessary to find the augmenter diameter, D, from the augmenter area, A_m. The ratio A_m/A_p may be found from the following equation, the derivation of which is shown in Appendix B:

$$R^2T_c+R(T_c+T_p)+T_p\left\{1-\frac{1.405}{M_p^2}\ \frac{P_m}{P_p}\left(\frac{A_m}{A_p}\right)^2\left[\frac{A_p}{A_m}\eta\left(\frac{P_p'-P_o}{P_p}\right)-\left(\frac{P_m-P_o}{P_p}\right)\right]\right\}=0 \qquad \text{(V-8)}$$

For an engine nozzle velocity of Mach 1, and with no static pressure increase through the augmenter tube

$$\frac{P_m}{P_p}=1 \qquad \text{(V-9)}$$

Engine manufacturers provide total and static pressures for all engine types at each power setting. For this case,

$$\frac{P_p'-P_o}{P_p}=1.86-1 \qquad \text{(V-10)}$$

Since for this illustration it is assumed that the exhaust stack acoustic treatment imposes no pressure influence upon the augmenter gas flow,

$$\frac{P_m-P_o}{P_p}=0 \qquad \text{(V-11)}$$

This assumption requires that $P_m = P_o$.

Now, solving Equation (V-8), above, yields:

$$\frac{A_m}{A_p}=2.51$$

Since $D^2 = (4\,A_m)/\pi$, then

$$D=\sqrt{(6.25)(2.51)}=3.96$$

From Figure 28 in Appendix C selection of a momentum pumping efficiency, η, of 0.90 indicates

$$\frac{L}{D} \cdot \frac{A_p}{A_m - A_p} = 3.0$$

Then,

$$L = 3.0 \times D \left(\frac{A_m}{A_p} - 1 \right)$$

and for this case

$$L = 17.9$$

The augmenter must be approximately 18 ft long and 4 ft in diameter.

The following tabulation shows the variation in augmenter diameter and length for pumping ratios of 1.0, 1.5 and 2.0. Case No. 4 shows the results of calculations of augmenter length and pumping ratio when a specific augmenter diameter is required.

Case No.	Aircraft Nozzle Diameter Ft	Pumping Ratio R	$\frac{A_m}{A_p}$	Length L Ft.	Diameter D Ft.
1	2.5	1.0	2.51	17.9	3.96
2	2.5	1.5	3.55	36.0	4.71
3	2.5	2.0	4.76	61.5	5.45
4	2.5	1.03	2.56	18.7	4.0

4. Miscellaneous Cell Consideration

An important factor to consider before design finalization is, "Will the cell be adequate for future, larger engines?" Obviously, the cell cannot be enlarged without restrictions. However, consideration of future cell usefulness will avoid costly delays and modifications.

Next in design consideration is the engine room geometry. A typical J75 engine with afterburner is 252 in. long. The augmenter tube projects at an extended position 6 ft into the cell room, and the nozzle of the engine is usually placed approximately 6 ft forward of the augmenter tube inlet bellmouth. This means that the engine inlet is a total of 33 ft from the back wall of the test cell. If the cell room has a height of 15 ft, it would be wise to place the engine inlet 15 ft (approximately) downstream from the inlet duct of the intake system. Figure 25 presents dimensional layouts suggested by this design. With approximately 8 ft more for the inlet opening of the intake system, the total length of the cell room, then, might be 55 to 60 ft, not counting the exhaust treatment.

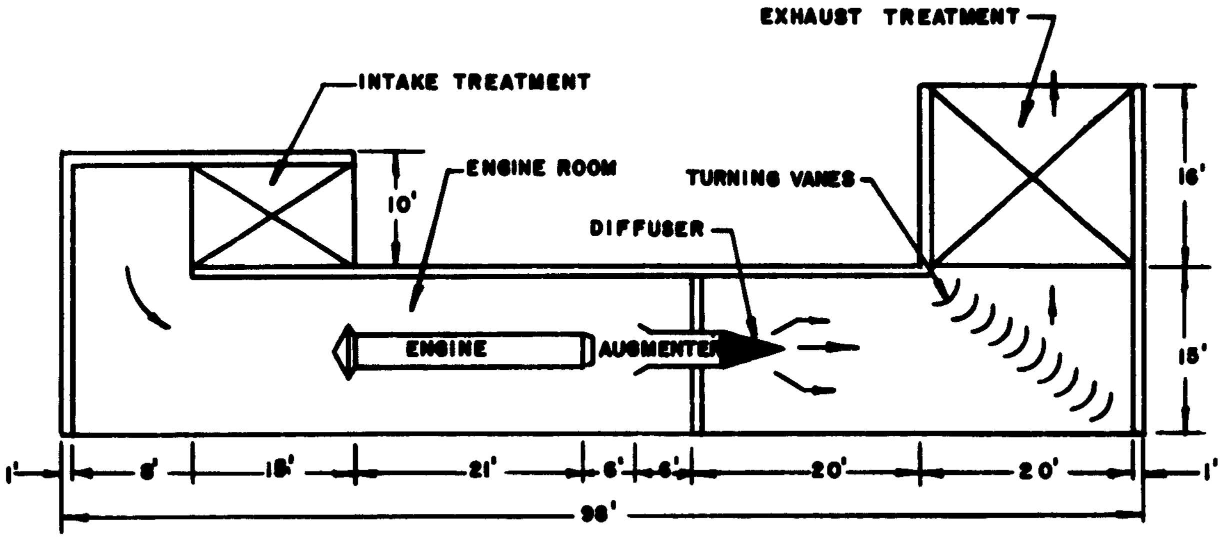


Figure 25. Some Typical Dimensions of a Test Cell

Adjustable engine dollies are sometimes mounted upon roller attachments. Position adjustments are made to fit the particular type of engine that is being tested in the cell. If engine mounts within the cell are of the non-adjustable type, the augmenter tube itself must be adjustable, especially if more than one type of engine is to be used in the cell. The design is finalized after engine positions are determined.

The length of the exhaust horizontal plenum chamber depends upon the need for additional noise reduction, availability of space, and the availability of funds for construction. A typical horizontal length between the back wall of the test room and the exhaust stack front wall, as shown in Figure 25, is 20 ft. Add to this the length of the stack which, for afterburner operation, is at least 20 ft for a 15-ft wide cell. The total length, then, from the back wall of the test cell room to the back wall of the stack is 40 ft. This makes the overall length of the test cell 95 to 100 ft.

Finally, the ideal size for the cross-section of the engine room can be determined using the information discussed in the examples of Section V-B-2.

In summary, the following general statements can be made. Cell exhaust flow conditions determine the design of the exhaust system. Then, augmenter pumping, cell room pressure, and flow requirements control the intake and engine room designs. Since augmenter pumping requirements are dictated by the exhaust flow limitations, the cell designer must consider the exhaust system first, the augmenter and diffuser next, and then the engine room and the intake system in that sequence.

SECTION VI

SUGGESTED INSTRUMENTATION FOR FACILITY NONACOUSTICAL EVALUATION

A test cell may be evaluated aerodynamically in terms of its effect upon engine performance, or in terms of its environmental duration·from ambient, or both. Specific cell limitations, if existent, should be defined by either method. This section will describe and discuss the instrumentation required to perform these evaluations.

Parts A through H discuss instrumentation for measurement of engine parameters, and Parts I through K discuss instrumentation for measurement of the cell environment. Each type of engine placed within the cell has its own set of operating parameters. It is necessary that a complete performance evaluation of cell-engine relationships be made for each type.

It is possible that two engines of the same type will have somewhat different operating characteristics when placed in a given cell. Thus, additional periodic evaluations should be made when large numbers of the same engine type are tested in a given cell.

The information discussed below is summarized in Table 1 of Appendix F.

A. Engine RPM

Engine speed is found by using a tachometer which provides the instantaneous speed (and speed variations) of the engine.

For test purposes it is also recommended that the average speed of the engine be determined by using a positive driven counter with the total number of revolutions of the engine counted during a timed period of test.

Both instruments are extremely important in that the speed variations immediately indicate operating stability, stall margins and performance in general. A revolution counter is necessary however, to accurately determine the average engine speed for use in power and efficiency calculations.

Generally a tachometer may be accurate within $\pm$ 2 to 3 percent, whereas a revolution counter and stop watch are accurate to within a fraction of one percent.

B. Exhaust Gas Temperature

Temperature measurement in a moving stream is inherently difficult. Therefore caution must be used in the selection of the exhaust gas temperature sensing device.

It is recommended that a shielded Chromel-Alumel thermocouple be used. Accuracy within $\pm$ one percent can be realized with a properly calibrated unit. A direct recording galvonometer is usually used to give the time-temperature history of a test.

C. Fuel Flow

Fuel consumption is measured during testing to evaluate engine performance and efficiency. Generally, for efficiency calculations, total fuel flow over a period of time is used to provide average fuel consumption. Flow meters are used during tests, however, to provide approximate flow rates for spot checks.

Time histories and total flow are usually recorded from direct read-out gauges. Total fuel consumption is usually accurately measured within very small fractions of a percent.

D. Thrust

Thrust is measured by a device called a load cell. The sensing unit may be a strain gauge or a piezioelectric crystal, either of which provides an electrical signal variation which is proportional to the stress to which the element is subjected.

An engine may be mounted on a test stand with either flexure plate-type or bearing-type supports. The thrust is then proportional to the movement of these supports as the engine is operated at different power settings.

Thrust indication is usually printed on a paper chart, but sometimes a needle-type dial or a digital read-out is used. The digital-type thrust reading is probably the most preferred.

The range of the force measurement should be from approximately zero to the maximum cell capacity, which in some cases, may be as high as 50,000 lb. The accuracy of thrust measuring instrumentation should be compatible with the other instrumentation, that is $\pm$ one percent.

E. Engine Inlet and Exhaust Pressures

The ratio of the pressure at the compressor inlet to the pressure at the exhaust nozzle can be used to determine engine performance. This pressure ratio is often used as an identifying characteristic of a jet engine. Thus, it is vital that pressure measurements at these positions be obtained.

The pressure ratio is usually derived from measurements taken with pitot-static tubes used in conjunction with U-tube manometers. These small tube probes are placed at the recommended positions at the entrance and exhaust of the engine. The ambient pressure is usually taken as the pressure in the control room, since this represents the environment under which the engine is operating.

The range of total pressure measurements for P_{T7} and P_{T2} should be from zero to 100 in. of mercury. Accuracy should be at least $\pm$ one percent of the pressure reading when the mercurial manometer is used. The accuracy varies from one percent to three percent for the bourdon tube or aneroid type gauge.

F. Engine Inlet Air Temperature

Engine inlet air temperature may be measured with a resistance-bulb sensing device. The change in resistance then is interpreted at a dial or digital readout in the control room as a temperature change. Paper-and-pen recorders are occasionally used to give the time history of this temperature. Sometimes thermocouples are used. The range of temperatures to be measured is from approximately -60° to +130°F. The accuracy of this temperature measurement should be comparable to other instrumentation previously discussed.

It should be re-emphasized that the inlet air temperature is a vital part of engine performance. Inlet temperature should be measured at a minimum of four positions around the entrance to the compressor. Usually the sensing devices are evenly spaced in the four quadrants at 90-degrees apart. As discussed in Section III of this volume, the inlet air temperature is used to correct performance parameters to specific altitudes or standard-day conditions for comparison with expected operation performance.

G. Timer

It is advisable to use a timing device to record the length of time that an engine is operated within a cell for a given run. A timer that will be turned on automatically when the engine is started and off when the engine stops is most appropriate. This can be done by an electronic switch activated by the engine ignition switch or by the RPM measurement system or by some other measuring device that indicates the engine is operating. The timer itself should be an electrically operated clock mechanism with a sweep-second hand. It should have a reset adjustment for 1 to 60 minutes on an inner scale and 1 to 60 seconds on an outer scale.

H. Vibration Indicator

Following engine repairs or parts replacement it is advisable to monitor engine vibration. Such vibration indicates the degree of balance of the rotors and the smoothness of operation of the compressor, the burner, and the turbine sections. The accelerometer is usually a spring-type displacement-sensing (electro-mechanical) device. The amplitude measured is generally in the range of 0.001 to 0.5 in. over the spectrum from 0 to 500 cps with an accuracy of $\pm$ 2 to 5 percent.

I. Barometric Pressure

The barometric (or ambient) pressure inside and outside of the cell is usually measured with an aneroid-type sensing device. This device has cells which are partially evacuated and sensitive to outside pressure. The pressure change causes a mechanical movement of a diaphragm which moves an indicator needle across a dial. Another more accurate type, of course, is the mercurial standard barometer. However, for most operational cells, the aneroid-type barometer is sufficiently accurate. The range of the barometric pressure to be measured will be from 26.0 to 31.8 in. of mercury. The accuracy of atmospheric pressure measurements should be within 0.5 percent or approximately 0.15 in. of mercury.

J. Test Cell Depression

Test cell depression is the measurement of pressure difference between the inside of the engine room and the outside of the cell. It is actually the measurement of the pressure loss through the intake treatment. This pressure may be measured with a U-tube manometer. Water is utilized here since the difference in the pressure is of small magnitude and could not be read accurately with a mercurial manometer. Mechanical (Bourdon tube) sensors and electromechanical transducers are also available for measuring pressure variations but the relatively low pressure variations are difficult to measure accurately with such devices. The accuracy should be $\pm$ 0.1 to 0.5 in. of water. Pressures may be expected to vary less than 20 in. of water against buffeting due to the velocity of the airflow through the engine room. The static pressure element should be located in the forward area of the engine room, ahead of the engine bellmouth.

K. Ambient Temperature

Measurement of temperature within the cell room is needed to fully evaluate the performance of a cell.

The temperature sensing device is usually a resistance-bulb thermometer using a dial digital readout or graphic recorder. In some instances a standard-type thermometer can be used in the cell and read visually. The range of temperature that may be expected is $-60^{\circ}F$ to $+150^{\circ}F$. The instrumentation should be accurate to $\pm$ 0.5 percent.

L. Miscellaneous Instrumentation

For cells in which engine functions approach marginal or critical operation, more detailed cell evaluations should be made. Additional instrumentation should measure engine room relative humidity (wet bulb temperature along with ambient temperature), dynamic pressures along the sides of the engine, secondary air velocities, and mixed gas temperatures.

SECTION VII

CONCLUSIONS

This report, entitled "Influence of Noise Control Components and Structures on Turbojet Engine Testing and Aircraft Ground Operation" has presented information to aid in the design, modification, or evaluation of test cells and suppressors. New test cells should be so designed as to exert a definable or negligible influence on the operation of a turbojet engine. Old cells may be evaluated and, if necessary, modified to allow accurate engine testing.

Cell aerodynamic and thermodynamic design should first consider flow and environmental requirements. This consideration leads to a determination of augmenter design. Augmenter design dictates intake and engine room dimensions. Typical cell design calculations have been presented to help describe this process.

Some design deficiencies may be avoided by:

(1) Providing sufficient flow area through the exhaust stack to accommodate the largest engine to be tested

(2) Providing adequate pumping of secondary air

(3) Reducing the cell depression by maintaining low intake velocities.

REFERENCES

1. Doelling, N. and the Staff of Bolt Beranek and Newman, Inc., Noise Control for Aircraft Engine Test Cells and Ground Run-Up Suppressors; Vol. I Measurement and Analysis of Acoustical Performance, WADC Technical Report 58-202, Vol. I Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio, November 1961.

2. Doelling, N. and the Staff of Bolt Beranek and Newman, Inc., Noise Control for Aircraft Engine Test Cells and Ground Run-Up Suppressors; Vol. II Design and Planning for Noise Control, WADC Technical Report 58-202, Vol. II, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio, November 1961.

3. Doelling, N. and the Staff of Bolt Beranek and Newman, Inc., Noise Control for Aircraft Engine Test Cells and Ground Run-Up Suppressors; Vol. III An Engineering Analysis of Measurement Procedures and Design Data, WADC Technical Report 58-202, Vol. III Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio, November 1961.

4. Durham, F. P., Aircraft Jet Powerplants, Prentice-Hall, Inc., Edgewood Cliffs, New Jersey, 1957.

5. Report PD-30, F89 Ground Noise Muffler, Northrup Aircraft, Inc., Hawthorne, California, 1958.

6. Investigation of Effects of Inlet Air Flow Distortion on the Performance of XJ79-GE-1 Turbojet, Engine Test Facility Report, AEDC-ETF-PDR-56-120, Arnold Engineering Development Center, Tullahoma, Tennessee, September, 1956.

7. Hussmann, A. W., Eductor Design Manual for Straight-Walled Ventilation Eductors in Gas Turbine Exhaust Stacks, Pennsylvania State College, Department of Engineering Research, prepared for US Navy Bureau of Ships, Contract No. NObs-56173, Index No. NS 622-078, May 1953.

APPENDIX A

CORRECTION FOR MEASURED THRUST DUE TO RAM PRESSURE IN TEST CELLS

Introduction

The ram pressure, or pressure due to velocity, created in jet engine test cells synthesizes conditions that would be experienced by the test engine if it were moving through the air. In order to obtain true sea level static thrust, or gross thrust, a correction factor for this ram pressure must be applied to the thrust measured by means of the thrust stand. Since this correction factor is a function of flow it will, obviously, vary with cell and engine size.

It is expected that cell ram pressure corrections will be in the vicinity of 2 percent to 3 percent of measured thrust. This amount is not as infinitesimal as it may at first appear when one considers that it is often desired to compare engine design changes which are expected to effect performances as little as 1/2 percent.

Nomenclature

The identification of parameters is as follows:

A = cross-sectional area, ft^2

F_i = indicated thrust, lb

F_g = gross thrust (true static thrust) lb

g = acceleration due to gravity, ft/sec^2

P = static pressure, lb/ft^2

P' = total pressure, lb/ft^2

R = ratio of cooling air to primary air

v = velocity, ft/sec

W = weight flow, lb/sec

$\mathcal{N}$ = cell ram pressure correction factor

ρ = density of air, $slugs/ft^3$

The following locations or conditions are indicated by the subscripts to areas, pressures, velocities, weight flows, and air densities (see Figure 26):

c = cooling air surrounding engine exhaust nozzle

p = primary air at engine exhaust nozzle

s = standard-day condition at sea level

t = test cell initial air (forward of engine)

Derivation

A ram pressure correction is needed to obtain the true static thrust of an engine within a test cell. It may be derived from a momentum-force balance equation between a cell cross-sectional plane forward of the engine and one at the engine exhaust nozzle. These planes are shaded in the partial sketch of a typical test cell shown in Figure 26.

Assuming uniform, parallel flow exists over Planes t and c, the momentum-force balance equation may be written

$$\frac{W_t}{g} v_t + A_t P_t + F_1 = \frac{W_c}{g} v_c + A_c P_c + \frac{W_p}{g} v_p + A_p P_p \qquad (1)$$

Since the equation for gross thrust is

$$F_g = \frac{W_p}{g} v_p + A_p (P_p - P_t') \qquad (2)$$

Equation (1) may be rewritten

$$F_g + A_p P_t' = F_1 + \frac{W_t}{g} v_t + A_t P_t - \frac{W_c}{g} v_c - A_c P_c \qquad (3)$$

Incorporating the definition for weight flow,

$$W = g \rho v A$$

Equation (3) may be rewritten

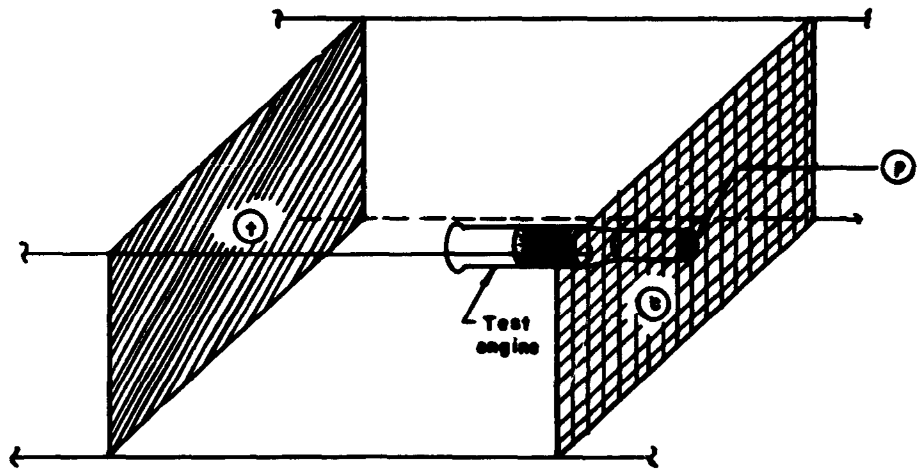
$$F_g + A_p P_t' = F_1 + \frac{W_t v_t}{2g} + \frac{(g \rho_t v_t A_t) v_t}{2g} + A_t P_t - \frac{W_c v_c}{2g} - \frac{(g \rho_c v_c A_c) v_c}{2g} - A_c P_c$$

or

$$F_g + A_p P_t' = F_1 + \frac{W_t v_t}{2g} + \frac{1}{2} \rho_t v_t^2 A_t + A_t P_t - \frac{W_c v_c}{2g} - \frac{1}{2} \rho_c v_c^2 A_c - A_c P_c \qquad (4)$$

Assuming all cell air flow incompressible, andutilizing the dynamic pressure equation

$$P' - P = \frac{1}{2} \rho v^2$$



NOTE: $Area_t = Area_c + Area_p$

Figure 26. Test Cell Cross Sections Indicated by Subscripts

Equation (4) becomes

$$F_g + A_p P_t' = F_i + \frac{W_t v_t}{2g} + A_t(P_t' - P_t) + A_t P_t$$

$$- \frac{W_c v_c}{2g} - A_c(P_c' - P_c) - A_c P_c$$

or

$$F_g + A_p P_t' = F_i + \frac{W_t v_t}{2g} + A_t P_t' - \frac{W_c v_c}{2g} - A_c P_c' \qquad (5)$$

Since it may be assumed that there is negligible total pressure loss of the cooling air between Planes (t) and (c), and since $A_t = A_c + A_p$

$$F_g = F_i + \frac{W_t v_t}{2g} - \frac{W_c v_c}{2g}$$

Since $R = W_c/W_p$, $W_t = W_p + W_c$, and $v = W/g\rho A$, then

$$F_g = F_i + \frac{W_p^2}{2g^2 \rho_t A_t} \left[(R + 1)^2 - R^2 \frac{\rho_t}{\rho_c} \frac{A_t}{A_c} \right] \qquad (6)$$

In order to relate measured test cell parameters to standard-day sea level conditions, the following equality is used:

$$\frac{\rho_t}{\rho_s} = \frac{P_t}{P_s} \frac{T_s}{T_t} = \frac{\delta}{\theta}$$

Therefore,

$$\rho_t = \rho_s \frac{\delta}{\theta} = 0.002379 \frac{\delta}{\theta}$$

The following terms of Equation (6) may be taken as a constant

$$\frac{1}{2g^2 \rho_t} = 0.2131 \frac{\theta}{\delta} \qquad (7)$$

Also

$$\frac{\rho_t}{\rho_c} = \frac{P_t T_c}{P_c T_t}$$

The true sea level static thrust is the ram pressure correction factor times the indicated thrust, or

$$\frac{F_g}{\delta} = \frac{F_i}{\delta} \mathcal{N}$$

$$= \frac{F_i}{\delta} \left\{ 1 + 0.2131 \frac{\left(\frac{W_p \sqrt{\theta}}{\delta} \Big/ A_t \right)}{\left(\frac{F_i}{\delta} \Big/ \frac{W_p \sqrt{\theta}}{\delta} \right)} \left[1 + 2R + R^2 \left(1 - \frac{A_t P_t T_c}{A_c P_c T_t} \right) \right] \right\}$$

Thus,

$$\mathcal{N} = 1 + 0.2131 \frac{\frac{W_p \sqrt{\theta}}{\delta} \Big/ A_t}{\frac{F_i}{\delta} \Big/ \frac{W_p \sqrt{\theta}}{\delta}} \left[1 + 2R + R^2 \left(1 - \frac{A_t P_t T_c}{A_c P_c T_t} \right) \right] \quad (8)$$

Most test cells are large enough so that P_t/P_c, T_c/T_t, and A_t/A_c are all nearly equal to unity. Assuming

$$\frac{A_t P_t T_c}{A_c P_c T_t} = 1$$

and incorporating this simplification, the equation for the ram pressure correction factor becomes

$$\mathcal{N} = 1 + 0.2131 \frac{\left(\frac{W_p \sqrt{\theta}}{\delta} \Big/ A_t \right)}{\left(\frac{F_i}{\delta} \Big/ \frac{W_p \sqrt{\theta}}{\delta} \right)} (2R + 1) \quad (9)$$

A first order approximation to the ram pressure correction, by assuming $F_i/\delta = F_g/\delta$ in Equation (9), is as follows:

$$\mathcal{N} = 1 + 0.2131 \frac{\left(\frac{W_p \sqrt{\theta}}{\delta} \Big/ A_t \right)}{\left(\frac{F_g}{\delta} \Big/ \frac{W_p \sqrt{\theta}}{\delta} \right)} (2R + 1) \quad (10)$$

Conclusions

The ram pressure correction, $\mathcal{N}$, for a given engine in a given cell may be calculated from Equation (9). The components W_p and F_g/W_p may be taken as rated military values (i.e., they are stamped on each engine). The test cell area, A_t, is easily determined. Air flow ratio, R, may be calculated from temperature and pressure measurements by the method presented in Appendix D. The ratio will, of course, vary with different engine-cell combinations.

Verification of the correction equation has been established by unpublished data of the General Electric Company's Jet Engine Department, Test Development Unit. A typical ram pressure correction calculated by means of Equation (9) of this report is approximately 0.2 percent lower than that actually measured during the General Electric testing program. This slight difference is probably due to the several approximations used in the derivation. The difference should be negligible since it is only about 5 percent to 10 percent of a 3 percent quantity.

APPENDIX B

EQUATIONS FOR PREDICTING TEST CELL AIR FLOW PERFORMANCE

Nomenclature

The identification of parameters is as follows:

A = cross-sectional area, ft^2

c = speed of sound, ft/sec

$C_{p(c \rightarrow m)}$ = specific heat of cooling air being heated from T_c to T_m, (Btu/lb)/°F

$C_{p(p \rightarrow m)}$ = specific heat of cooling air being cooled from T_p to T_m, (Btu/lb)/°F

g = acceleration due to gravity, ft/sec^2

M = Mach number

P = static pressure, lb/ft^2

P' = total pressure, lb/ft^2

R = ratio of cooling air to primary air

T = temperature, °R

v = velocity, ft/sec

W = weight flow, lb/sec

η = momentum pumping efficiency factor

ρ = density of air, $slugs/ft^3$

The following locations or conditions are indicated by the subscripts:

c = cooling air

m = mixed air at augmenter exit

o = atmospheric condition

p = primary air at engine exhaust

s = standard-day condition at sea level

Fundamental Pumping Equation

The derivation of parameters for flow through the augmenter of a jet engine suppressor utilizes the fundamental continuity equation. The general equation is:

$$W = \rho g v A$$

Specifically, relating the weight flow out of the augmenter to that out of the engine,

$$\frac{W_m}{W_p} = \frac{\rho_m v_m A_m}{\rho_p v_p A_p}$$

Since it is desirable to solve for weight flow in terms of R, the ratio of cooling air to primary air, and since $W_m = W_p + W_c$, then

$$1 + R = \frac{\rho_m v_m A_m}{\rho_p v_p A_p} \tag{1}$$

Derivation of Gas Ejector Equation

Since the Mach numeber of a jet engine is usually known or can easily be calculated knowing pressure ratios, the primary velocity may be derived by the following equation:

$$v_p = M_p c_s \sqrt{\frac{T_p}{T_s}} \tag{2}$$

The velocity out of the augmenter is less simple but may be found from the equation for dynamic pressure where

$$P_m' - P_m = \frac{1}{2} \rho_m v_m^2$$

Solving for velocity,

$$v_m = \sqrt{\frac{2}{\rho_m} (P_m' - P_m)} \tag{3}$$

Substituting Equation (2) and (3) terms in Equation (1),

$$1 + R = \frac{\rho_m}{\rho_p} \sqrt{\frac{2}{\rho_m}} \frac{\sqrt{P_m' - P_m}}{M_p c_s} \sqrt{\frac{T_s}{T_p}} \frac{A_m}{A_p}$$

Considering that density is proportional to static pressure and inversely proportional to temperature, the known standard-day density, ρ_s, will aid in the solution. Thus,

$$1 + R = \sqrt{\frac{2\rho_s \frac{T_s P_m}{P_s T_m}}{\rho_s \frac{T_s P_p}{P_s T_p}{}^2}} \sqrt{\frac{P_m' - P_m}{M_p c_s}} \sqrt{\frac{T_s}{T_p}} \frac{A_m}{A_p}$$

or

$$1 + R = \sqrt{\frac{2}{\rho_s} \frac{T_p}{T_m} \frac{P_s P_m}{P_p P_p}} \frac{\sqrt{P_m' - P_m}}{M_p \quad c_s} \frac{A_m}{A_p} \tag{4}$$

Assuming a negligible augmenter entrance loss and negligible friction loss through the augmenter, a good substitution may be made for P_m', the total pressure at the augmenter exit. The force at the jet engine exhaust equals the force at the augmenter exit when the augmenter has been geometrically designed to allow complete mixing of the air flows. If this ideal geometric configuration does not exist, a momentum pumping efficiency factor needs be applied. This mixing factor, η, is the ratio of the actual momentum leaving the augmenter to the theoretical momentum under ideal conditions. Recalling that force is equal to pressure times area, and relating the pressure at both locations to outside pressure,

$$(P_p' - P_o)A_p\eta = (P_m' - P_o)A_m$$

or

$$P_m' = (P_p' - P_o)\eta \frac{A_p}{A_m} + P_o \tag{5}$$

Little is known of the mixing factor other than what empirical data can provide. Model testing has shown that the mixing factor has a definite variance on the augmenter length over diameter ratio divided by the system area ratio. It may be expected that other parameters may subject an influence, but a definite trend may may be determined from a plot of $\frac{L}{D} \cdot \frac{A_p}{A_m}$ versus η. When the geometric ratio becomes smaller than 1.0, then factor decreases rapidly indicating a poor efficiency. As $\frac{L}{D} \cdot \frac{A_p}{A_m}$ becomes somewhat greater than unity, η approaches 1.0 (or 100 percent).

Substituting Equation (5) in Equation (4) and squaring both sides,

$$(1 + R)^2 = \frac{2}{\rho_s} \frac{T_p}{T_m} \frac{P_s}{P_p} \frac{P_m}{P_p} \left[\frac{\frac{A_p}{A_m}\eta(P_p' - P_o) - P_m - P_o}{M_p{}^2 \, c_s{}^2}\right]\left(\frac{A_m}{A_p}\right)^2 \tag{6}$$

Inserting the following constants

$$\rho_s = .002379$$

$$c_s = 49.4 \quad T_s = 1125$$

$$P_s = 2116$$

Equation (6) becomes

$$(1 + R)^2 = \frac{1.405}{M_p^2} \frac{T_p}{T_m} \frac{P_m}{P} \left(\frac{A_m}{A_p} \right)^2 \left[\frac{A_p}{A_m} \eta \left(\frac{P_p 2 - P_o}{P_p} \right) - \left(\frac{P_m - P_o}{P_p} \right) \right] \tag{7}$$

<u>Adaptation of Ejector Equation for Jet Engine Test Cells</u>

The term T_m, the mixed temperature of the cooling air and primary air, can complicate Equation (7) for certain usages. There is no problem if the calculation is for a condition where a desired exit temperature has been established. In this case, the numerical value of the desired temperature will, doubtlessly, be inserted and the other parameters be appropriately adjusted.

If it is allowable that the mixed temperature fall within a wide range and certain other parameters are not flexible, then an additional equation must be used that will provide known parameters in substitution for T_m. This equation is provided by the fact that the heat gained by the cooling air equals the heat lost by the primary air. Incorporating the use of specific heats, it follows

$$W_c \, C_{p(c \to m)} \, (T_m - T_c) = W_p \, C_{p(p \to m)} \, (T_p - T_m)$$

The above equation assumes that after mixing the temperature is homogeneous. Solving for the desired term,

$$T_m = \frac{W_c \, C_{p(c \to m)} \, T_c + W_p \, C_{p(p \to m)} \, T_p}{W_c \, C_{p(c \to m)} + W_p \, C_{p(p \to m)}}$$

Assuring that for average jet conditions

$$\frac{C_{p(p \to m)}}{C_{p(c \to m)}} = \frac{0.30}{0.25} = 1.2$$

then

$$T_m = \frac{W_c \, T_c + 1.2 \, W_p \, T_p}{W_c + 1.2 \, W_p}$$

or, recalling that $R = W_c/W_p$,

$$T_m = \frac{RT_c + 1.2T_p}{R + 1.2}$$

Should the flow problem require substitution of Equation (8) in Equation (7), th solution for R will involve a third order improper fraction. Graphical means wi probably provide the simplest solution to finding the roots of such an equation.

For cold flow (or quick approximations), the specific heat ratio may be assumed to be 1.00. For cold flow, then,

$$T_m = \frac{RT_c + T_p}{R + 1} \tag{9}$$

Substituting Equation (9) in Equation (7) produces the quadratic in R (cold flow):

$$R^2T_c + R(T_c + T_p) + T_p \left\{1 - \frac{1.405}{M_p^2} \frac{P_m}{P_p} \left(\frac{A_m}{A_p}\right)^2 \left[\frac{A_p}{A_m} \eta \left(\frac{P_p' - P_o}{P_m}\right) - \left(\frac{P_m - P_o}{P_p}\right)\right]\right\} = 0 \tag{10}$$

APPENDIX C

MOMENTUM PUMPING EFFICIENCY AS RELATED TO AUGMENTER GEOMETRY

Nomenclature

The identification of parameters is as follows:

A = cross-sectional area, ft^2

c = speed of sound, ft/sec

$C_{p(c \rightarrow m)}$ = specific heat of cooling air being heated from T_c to T_m (Btu/lb)/°F

$C_{p(p \rightarrow m)}$ = specific heat of cooling air being cooled from T_p to T_m (Btu/lb)/°F

D = augmenter diameter, ft

g = acceleration due to gravity, ft/sec^2

L = augmenter length, ft

M = Mach number

P = static pressure, lb/ft^2

P' = total pressure, lb/ft^2

R = ratio of cooling air to primary air

T = temperature, °F

v = velocity, ft/sec

W = weight flow, lb/sec

η = momentum pumping efficiency factor

ρ = density of air, $slugs/ft^3$

The following locations or conditions are indicated by the subscripts:

c = cooling air

m = mixed air at augmenter exit

o = atmospheric condition

p = primary air at engine exhaust

s = standard-day condition at sea level

General Discussion

Air flow performance within a jet engine test cell is greatly effected by augmenter design. In order to aid in the design of proper augmenter tubes for use in test cells, equations for predicting test cell air flow performance have been developed.

An equation for determining the pumping ratio of a test cell is

$$R^2T_c + R(T_c + T_p) + T_p \left\{ 1 - \frac{1.405}{M_p^2} \frac{P_m}{P_p} \left(\frac{A_m}{A_p}\right)^2 \left[\frac{A_p}{A_m} \eta \left(\frac{P_p' - P_o}{P_p}\right) \left(\frac{P_m - P_o}{P_p}\right)\right]\right\} = 0 \tag{1}$$

In deriving equations for air flow through augmenter tubes, consideration must be given the degree of efficiency with which primary and secondary flows are mixed. This pumping efficiency factor, η , is primarily a function of geometric design. As it appears in Equation (1), η is the ratio of the actual momentum leaving the augmenter tube to the theoretical momentum under ideal conditions. Little is known of this efficiency factor other than what empirical data can provide. Model testing was conducted at Kittell-Lacy to determine the manner and extent which η is dependent on other augmenter parameters.

Test Procedures

Tests to determine momentum pumping efficiency factors were conducted using a jet engine simulator. The jet engine simulator is capable of exhausting at velocities in excess of 2000 ft/sec and at temperatures in excess of 3000°F. The simulator used has a 5-inch diameter exhaust nozzle. A typical test setup with a model augmenter tube behind the jet engine simulator is shown in Figure 27. A manometer board was used for measuring total and static pressures in the air flow system by means of pitot tubes. In collecting the data, the mass flow of the simulator was measured in the 6-inch diameter duct upstream from the combustion chamber. The final flow out of the augmenter tube was measured at the exit end of the augmenter tube. Data for approximately sixteen probe locations were taken at the exit end of the augmenter. These measurements included total pressure, static pressure, and temperature. Tests were run with augmenter tubes of various diameters and various lengths. During these tests, the static pressure change across the augmenter tube was varied. It was observed that a change in static pressure would have little effect on the pumping efficiency. These tests were conducted at jet engine simulator exhaust temperature settings ranging from 120°F to approximately 3000°F. The jet engine simulator exit velocities were varied between approximately 300 and 2000 ft/sec.

Analysis of Data

The test data showed the momentum pumping efficiency factor, η , to be a function of the geometric configuration of the augmenter tube, namely

$$[L/D] \cdot [A_p/(A_m - A_p)]$$

Within the range that these tests were conducted, other factors did not appreciably influence the pumping efficiency.

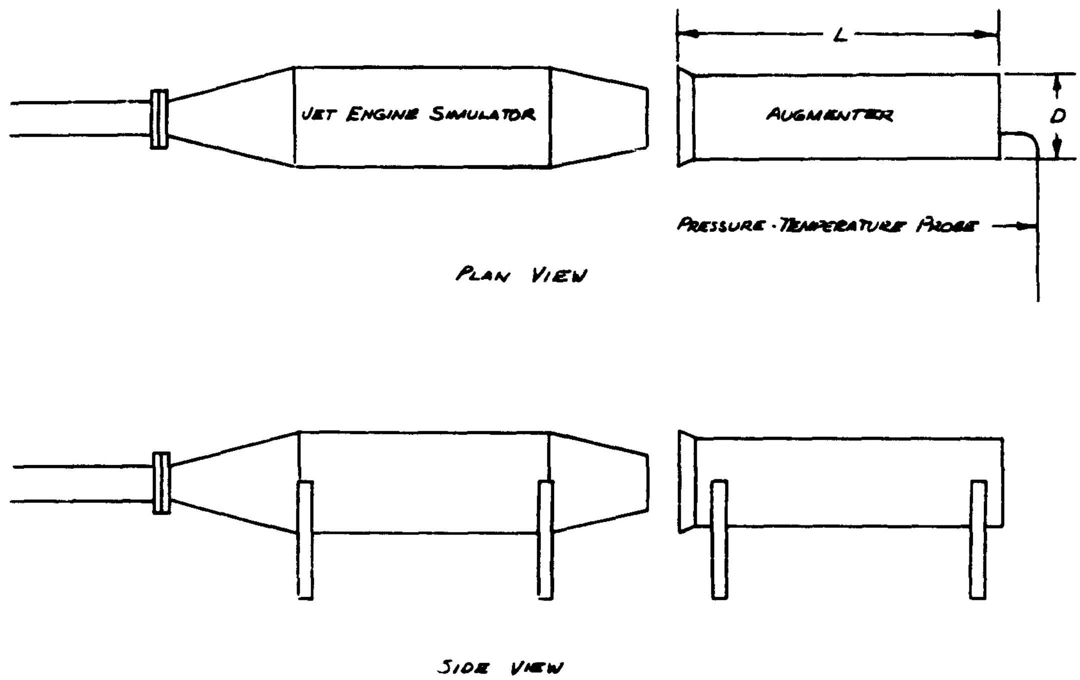


Figure 27. Model Augmenter Tube with Jet Engine Simulator

A plot showing η versus $[L/D] \cdot [A_p/(A_m - A_p)]$ is presented in Figure 28. It may be observed from Figure 28 that the pumping efficiency factor will be nearly 1.0 if the augmenter geometric configuration is properly designed. However, the steep slope in the curve for values of $[L/D] \cdot [A_p/(A_m - A_p)]$ less than 1.0 indicates that the pumping efficiency will be very poor in this region. The curve shown in Figure 28 agrees quite well with data presented on Page 36 of Eductor Design Manual (Ref. 7) where the pumping efficiency factor, η, is presented in its inverse form and is termed M.

In planning augmenter tubes, a general rule-of-thumb is to design for an L/D of between 6 and 10. The ratio of augmenter area to jet exhaust nozzle area, A_m/A_p must primarily be designed to maintain sufficient flow through the test cell. This area ratio with respect to the desired test cell flow ratio can be calculated from Equation (1). An augmenter length can then be determined that will obtain satisfactory pumping efficiency. This efficiency can be determined by using the graph of Figure 28. It should be kept in mind, however, that the larger the augmenter to jet area ratio, the more difficult it will be to pump the air through those intake and exhaust acoustic treatments which yield to a high back-pressure.

Table I presents typical momentum pumping efficiency values for various augmenter geometric combinations. The chart presents efficiency values for L/D from 6 to 10 with A_m/A_p from 2.0 to 10.

Conclusions

Model testing has determined that the only appreciable effect on momentum pumping efficiency through augmenter tubes is caused by variance of the geometric ratio $[L/D] \cdot [A_p/(A_m - A_p)]$. In order to maintain a momentum pumping efficiency greater than 80 percent, it is necessary that this geometric ratio be equal to or greater than 1.0. As shown in Figure 28, the momentum pumping efficiency, η, decreases very rapidly as the geometric ratio goes below 1.0. Using the pumping efficiency factor, the air flow performance of the augmenter section of the test cell can be calculated using Equation (1).

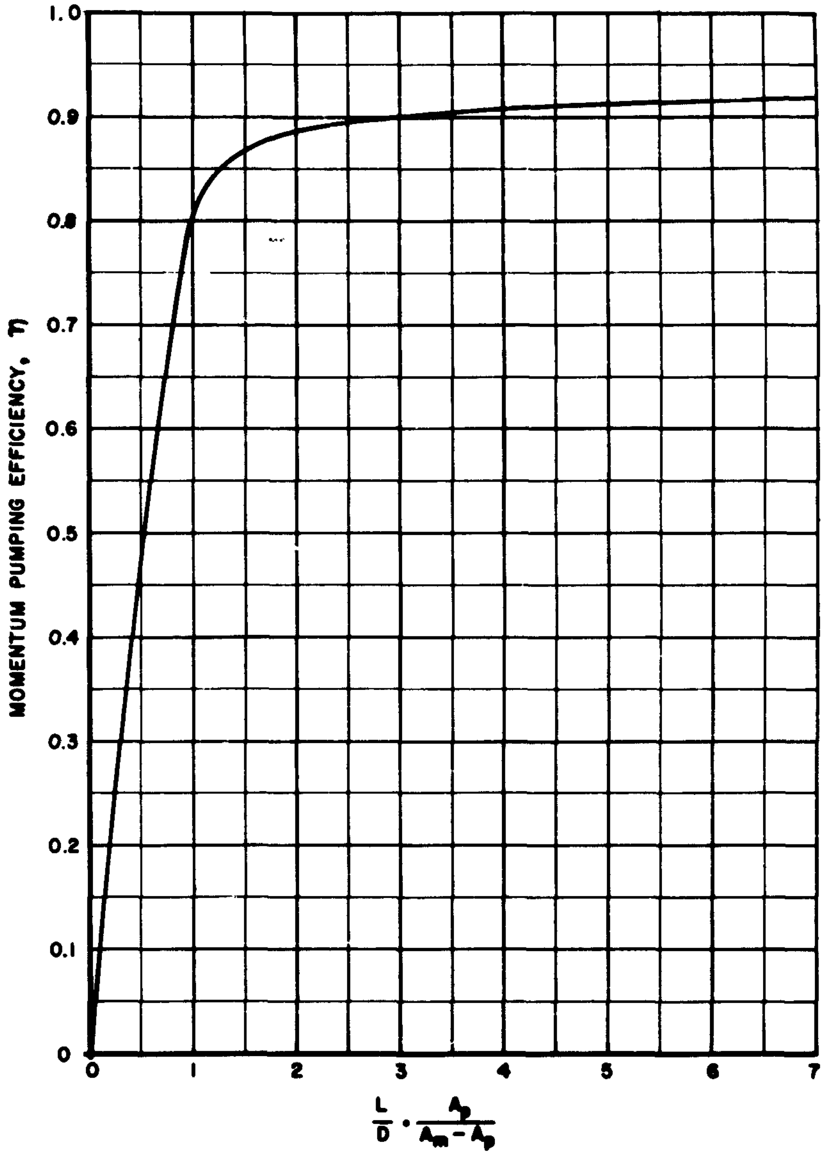


Figure 28. Augmenter Momentum Pumping Efficiency, η, as Related to Geometric Design

TABLE I

AUGMENTER MOMENTUM PUMPING EFFICIENCIES
FOR FREQUENTLY-USED GEOMETRIC RATIOS

Geometric Ratios	Momentum Pumping Efficiency, η				
$\frac{A_m}{A_p} \downarrow$ \ $\frac{L}{D} \rightarrow$	6	7	8	9	10
2	.917	.921	.923	.925	.926
3	.900	.904	.907	.910	.912
4	.886	.893	.897	.900	.902
5	.867	.878	.886	.892	.896
6	.843	.862	.872	.880	.886
7	.800	.838	.856	.867	.875
8	.725	.800	.834	.853	.863
9	.654	.740	.800	.832	.849
10	.595	.675	.745	.800	.828

APPENDIX D

THERMODYNAMIC CALCULATIONS

Nomenclature

$C_{p(c-m)}$ = Specific heat of cooling air being heated from T_c to T_m, $\frac{\text{Btu/lb}}{^{\circ}\text{F}}$

$C_{p(p-m)}$ = Specific heat of primary air being cooled from T_p to T_m, $\frac{\text{Btu/lb}}{^{\circ}\text{F}}$

$C_{p(m-f)}$ = Specific heat of mixed gas being cooled from T_m to T_f, $\frac{\text{Btu/lb}}{^{\circ}\text{F}}$

C_{p_s} = Specific heat of steam, $\frac{\text{Btu/lb}}{^{\circ}\text{F}}$

C_{p_w} = Specific heat of water, $\frac{\text{Btu/lb}}{^{\circ}\text{F}}$

GPM = Gallons per minute of water

L_w = Heat of vaporization of water, Btu/lb

R = Ratio of W_c to W_p

T_c = Initial temperature of cooling air, $^{\circ}$F

T_p = Initial temperature of primary air, $^{\circ}$F

T_m = Temperature of mixed gas with no water cooling, $^{\circ}$F

T_f = Final exhaust temperature, $^{\circ}$F

T_w = Initial temperature of cooling water, $^{\circ}$F

V_f = Volume flow of exhaust, ft^3/sec

ρ' = Volume of exhaust per pound of mixed exhaust air, ft^3/lb

W_c = Weight of cooling air, lb/sec

W_p = Weight of primary air, lb/sec

W_w = Weight of water, lb/sec

Analysis for Silencing With Water Cooling

The general equation for mixing the cooling air with the jet exhaust gas is

$$W_c C_{p(c-m)}(T_m - T_c) - W_p C_{p(p-m)}(T_p - T_m) = 0 \qquad \text{(A1)}$$

This equation assumes that after mixing the temperature is homogeneous. Solving for T_m, Equation (A1) becomes

$$T_m = \frac{W_c C_{p(c-m)} T_c + W_p C_{p(p-m)} T_p}{W_c C_{p(c-m)} + W_p C_{p(p-m)}}$$

Since R is defined equal to W_c/W_p, and assuming that

$$\frac{C_{p(p-m)}}{C_{p(c-m)}} = \frac{0.30}{0.25} = 1.2$$

the temperature before water cooling becomes

$$T_m = \frac{RT_c + 1.2T_p}{R + 1.2} \tag{A2}$$

After adding cooling water to the exhaust flow, it is assumed that all the water is vaporized and that T_f 212°F. The following relationships then hold:

$$(W_c + W_p)\ C_{p(m-f)}(T_m \quad T_f) - W_w\ [C_{pw}(212-T_w) + L_w + C_{p_s}(T_f - 212)] = 0 \tag{A3}$$

Since $W_c + W_p = (1 + R)W_p$, and assuming $C_{p(m-f)} = 0.26$, $W_w = \frac{GPM}{7.2}$,

$C_{p_w} = 1.0$, T_w 70, $L_w = 970$, and $C_{p_s} = 0.48$, Equation (A3) may be stated

$$T_f = \frac{0.26\ T_m(1 + R)W_p - \frac{GPM}{7.2}(142) - \frac{GPM}{7.2}(970) + \frac{GPM}{7.2}(0.48)(212)}{0.26\ (1 + R)W_p + \frac{GPM}{7.2}(0.48)}$$

or, more simply,

$$T_f = \frac{0.26T_m(1 + R)W_p - 140\ GPM}{0.26(1 + R)W_p + 0.067\ GPM} \tag{A4}$$

The volume flow is determined by

$$V_f = (W_c + W_p)\rho' \tag{A5}$$

where

$$\rho' = (T_f + 459)\left[.0253 + .0405\ \frac{W_w}{W_c + W_p}\right] \tag{A6}$$

Substituting Equation (6) in Equation (5) and replacing $(W_c - W_p)$ and W_w by the values previously stated,

$$V_f = .0253\ (T_f + 459)(1 + R)W_p + .0405\ (T_f + 459)\ \frac{GPM}{7.2} \qquad (A7)$$

Analysis for Silencing Without Water Cooling

For the operation of the jet engine test cell without water, T_m, is equal to T_f. Making this substitution in Equation (2), the final temperature is

$$T_f = \frac{RT_c + 1.2T_p}{R + 1.2} \qquad (A8)$$

The volume flow may be calculated from Equation (7) by making the substitution of GPM equals zero. Therefore, when no water cooling is used

$$V_f = .0253\ (T_f + 459)(1 + R)\ W_p \qquad (A9)$$

Calculation of Suppressor Design Requirements

The graphs used in the original design of the Truax Air Force Base noise suppressor are presented in this report (Figures 29 through 32). They are included for the purpose of showing a typical solution of the thermodynamic equations.

With Water Cooling. The silencer is designed to carry a maximum volume flow of approximately 31,000 ft^3/sec and a maximum final temperature of approximately 530°F when water cooling is used. It is assumed that these will be for afterburning operation and therefore not for sustained periods.

In order to simulate a typical set of conditions under which the cell would be required to operate, the following are assumed:

$$T_p = 3150^\circ F$$

$$T_c = 70^\circ F$$

$$W_p = 270 \text{ lb/sec}$$

Using Equation (4), gallons per minute of water are plotted against final temperature for various flow ratios in Figure 29. Then, with the use of Equation (7), gallons per minute of water are plotted against volume flow for various flow ratios in Figure 30. Figures 29 and 30 are then used to read the final temperature and volume flow at specific amounts of water. The final temperature versus volume flow are plotted in Figure 31 from which the design point may be located.

Without Water Cooling. When no water cooling is used, the silencer is designed to carry a maximum volume flow of approximately 22,000 ft^3/sec and a maximum final temperature of approximately 450°F. These values are lower than those assumed for water cooling cases, since it is assumed that runs not using water will be under military power and will last for longer duration.

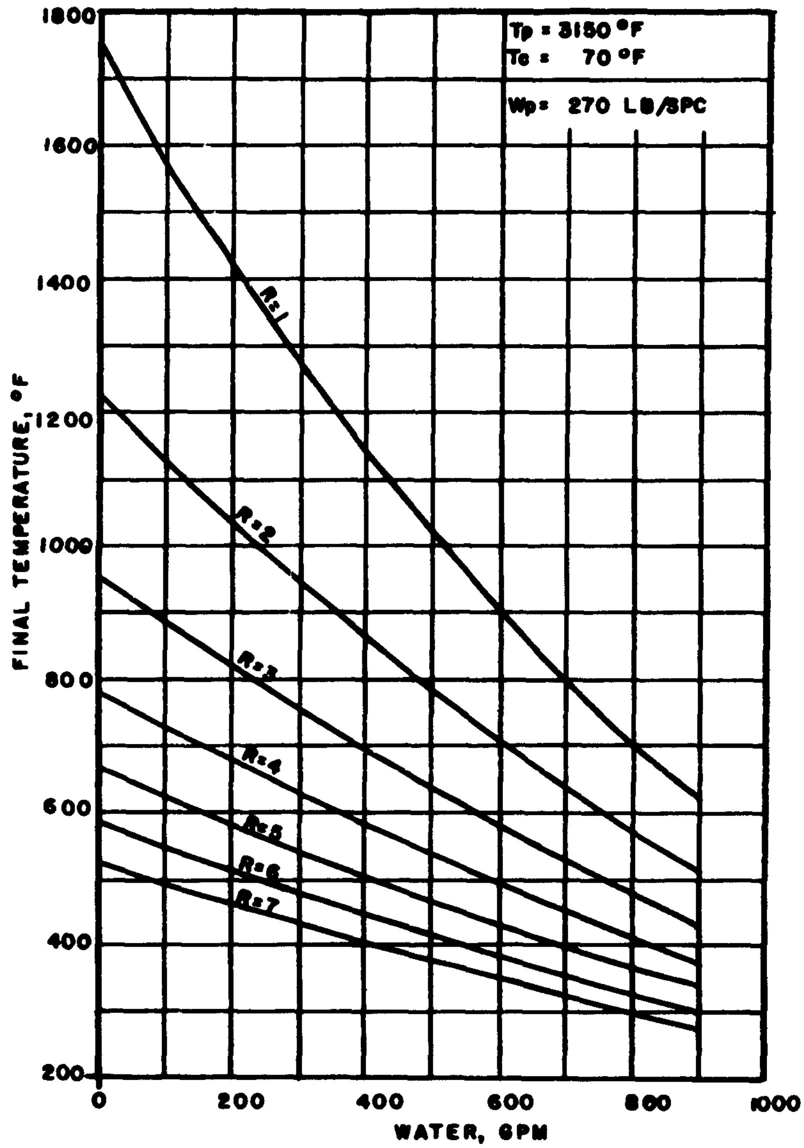


Figure 29. GPM Versus Final Temperature for Various Flow Ratios

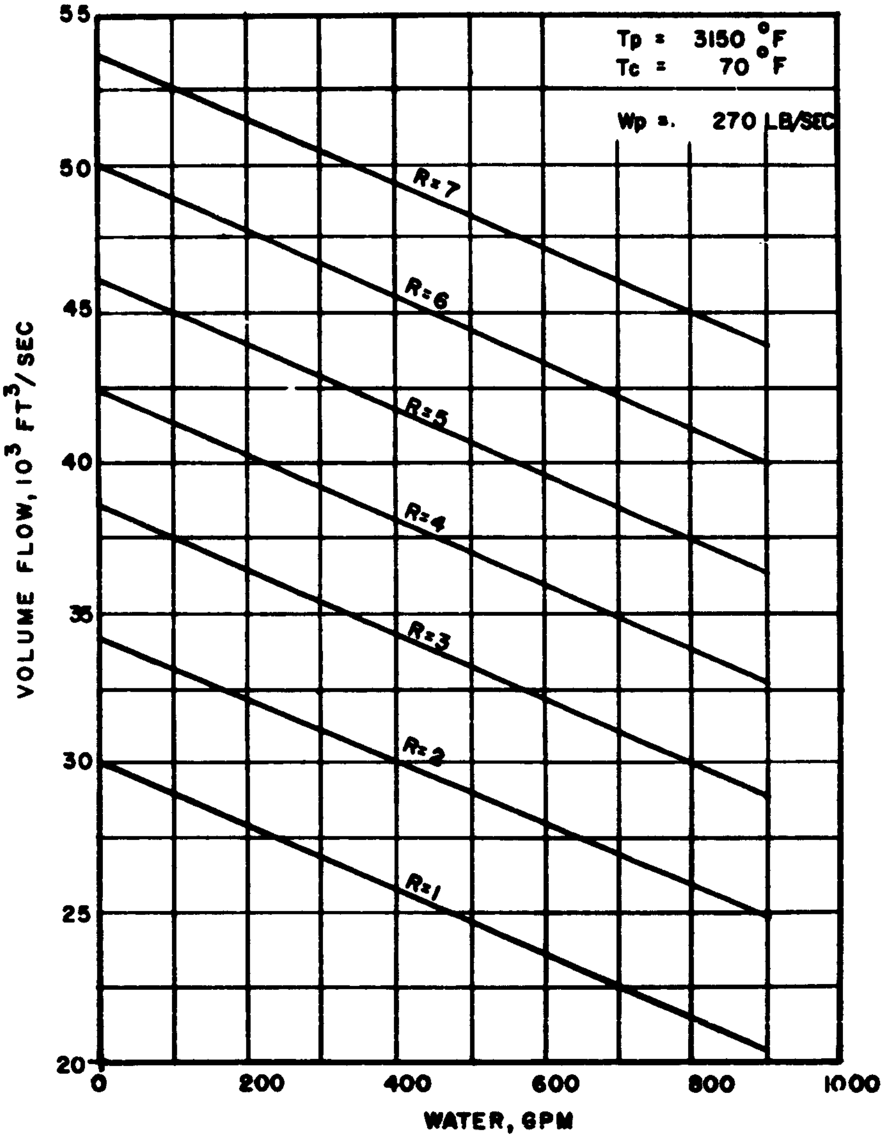


Figure 30. GPM Versus Volume Flow for Various Flow Ratios

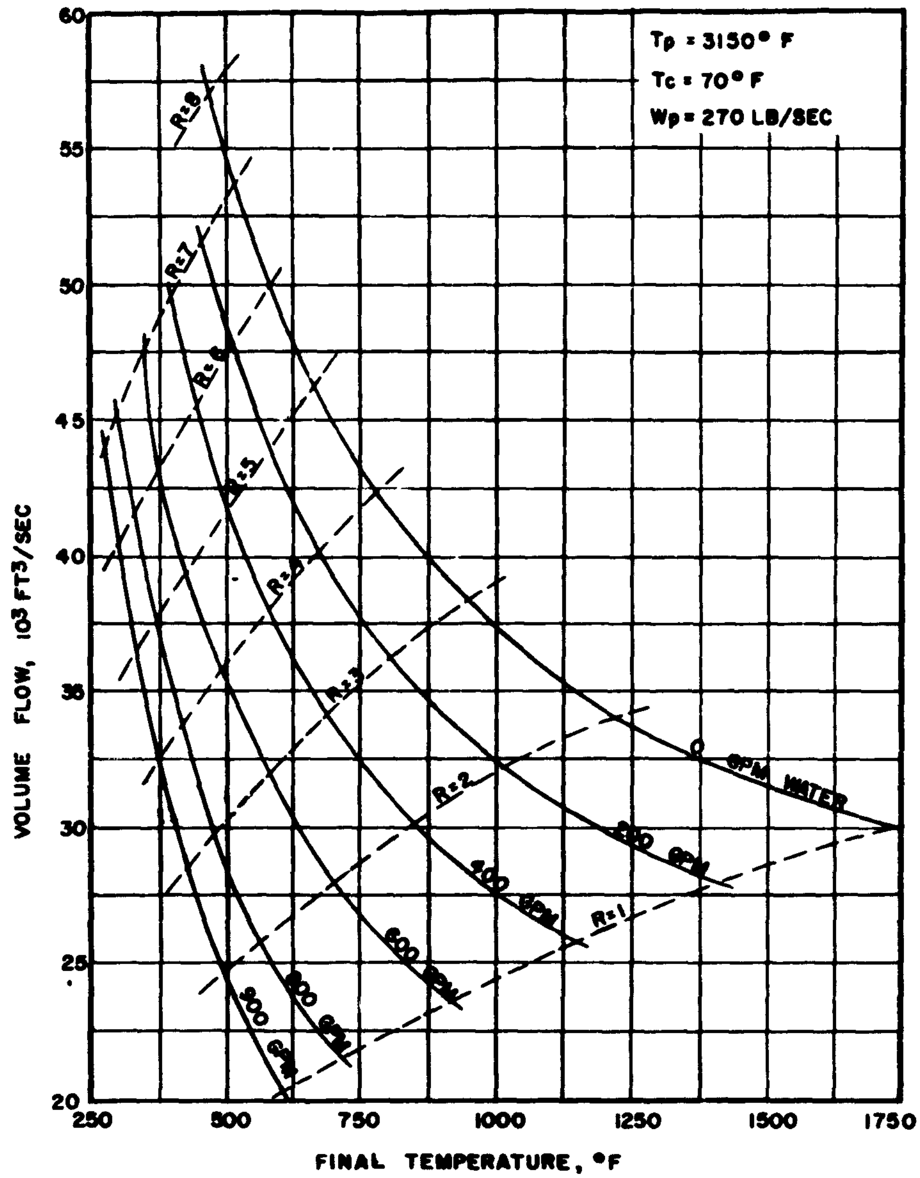


Figure 31. Final Temperature Versus Volume Flow for Varying Amounts of Water

In order to simulate a typical set of conditions under which the cell would be required to operate, the following are assumed:

$$T_p = 1300^{\circ}F$$

$$T_c = 70^{\circ}F$$

$$W_p = 260 \text{ lb/sec}$$

Using Equation (9), final temperature is plotted versus volume flow for various flow ratios in Figure 32. The flow ratio at which the design requirements are satisfied may be read on this curve.

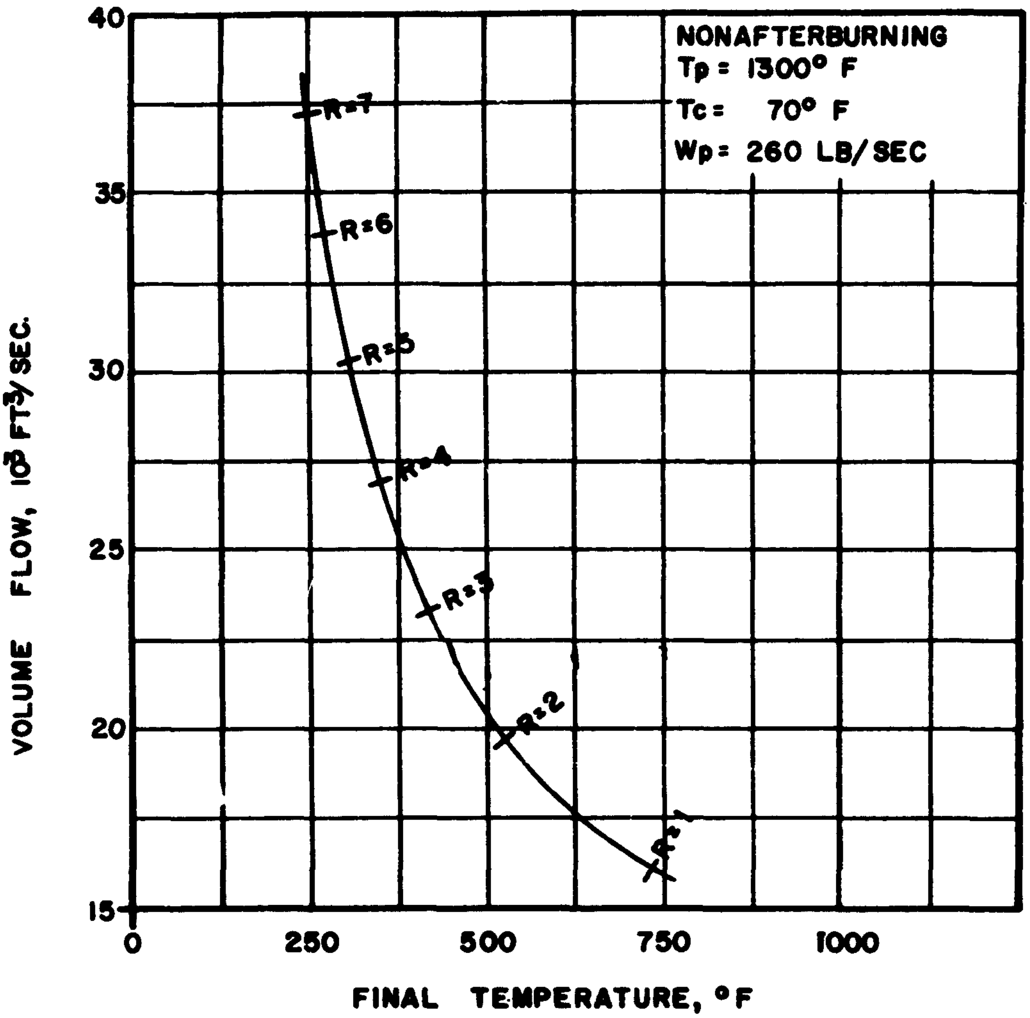


Figure 32. Final Temperature Versus Volume Flow for Cases Without Water Cooling

APPENDIX E

INSTRUMENTATION FOR NONACOUSTICAL TEST CELL EVALUATIONS

ENGINE OR CELL PARAMETER	TYPES OF SENSORS - READOUTS
A. Engine R.P.M. (N1 and N2) Percent Rev. Symbol "N"	A. Sensor - Counter, Timer and Revolutions Readout - Visual Meter (Dial) Digital Printed Chart Recorder
B. Exhaust Gas Temperature (E.G.T.) (°F) Range - 0 to 2400°F Symbol "T"	B. Sensor - Thermocouple, °Farenheit Readout - Visual Meter (Dial) Digital Printed Chart Recorder
C. Fuel Flow (P.P.H.) Range - 700 to 75,000 PPH Symbol "W_f"	C. Sensor - Flow Meter Readout - Visual Meter (Dial) Digital Printed Chart Recorder
D. Thrust (Pounds) Range - 0 to 50,000 (Cell Capacity Symbol "F"	D. Sensor - Load Cell Pressure Probes Indicating Pressure Ratios Readout - Visual Meter (Dial) Digital
E. Engine Pressures (Hg) Range - 0" to 100" Hg Symbol - P_{t_2} and P_{t_7} or "E.P.R." (Engine Pressure Ratio)	E. Sensor - Pitot-Static Tube Readout - U-Tube Manometer Mercurial Type
F. Engine Inlet Temperature (°F) Range - 60 to plus 150°F Symbol - "t_o"	F. Sensor - Resistance Bulb Thermocouple Standard Thermometer Readout - Visual Meter Digital Printed Chart

G. Timer (To Nearest 0.1 Second)	G. Sensor - Electric Clock Readout - Visual Meter
H. Vibration Indicator 0-500 CPS. 0-0.15" Displacement	H. Sensor - Accelerometer, Crystal or Electromechanical (displacement) Readout - Visual Meter Digital Printed Chart
I. Barometric Pressure (Hg) Range - 26 to 31.8" Hg Symbol "P_{am}"	I. Sensor - Barometer, Mercurial or Aneroid Readout - Visual Observation
J. Test Cell Depression (H_2O) Range - 10 to plus 10" H_2O	J. Sensor - Pressure Probe U-Tube Water Manometer Readout - Visual Observation
K. Ambient Temperature (^oF) Range - minus 60 to plus 150^oF Symbol - "t_{am}"	K. Sensor - Thermometer - Mercurial or Alcohol. Also Resistance Type Readout - Visual or Dial Meter

NOTE: Because of the availability of many acceptable manufacturers' instruments in each of the above categories, specific brands have not been named.

Aerospace Medical Division, 6570th Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio. Rpt. No. AMRL-TDR-62-134. INFLUENCE OF NOISE CONTROL COMPONENTS AND STRUCTURES ON TURBOJET ENGINE TESTING AND AIRCRAFT GROUND OPERATION. Final report, December 1962, vii + 97 pp. incl. illus., table, 7 refs.

Unclassified Report

There has been a need for summarizing and establishing adequate aerodynamic and thermodynamic design criteria for turbojet engine test cells and ground run-up suppressors. These criteria are discussed and their uses are illustrated by examples of typical design problem solutions. The

(over)

UNCLASSIFIED

1. Acoustics
2. Jet Engine Noise
3. Damping
4. Ground support equipment

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III. Contract AF 33(616)-5789
IV. Kittell-Lacy, Inc. El Monte, Calif.
V. Bonard E. Morse

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presence of noise suppression structures can have significant influences upon the operation of the turbojet engine. These influences are enumerated and evaluated with recommendations for establishing maximum acceptable effects. Typical test cell configurations are presented and design criteria are established for providing noise suppression facilities which may be utilized for testing a full size aircraft or an engine by itself. These facilities can be either permanent structures or portable units.

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Aerospace Medical Division, 6570th Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio. Rpt. No. AMRL-TDR-62-134. INFLUENCE OF NOISE CONTROL COMPONENTS AND STRUCTURES ON TURBOJET ENGINE TESTING AND AIRCRAFT GROUND OPERATION. Final report, December 1962, vii + 97 pp. incl. illus., table, 7 refs.

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There has been a need for summarizing and establishing adequate aerodynamic and thermodynamic design criteria for turbojet engine test cells and ground run-up suppressors. These criteria are discussed and their uses are illustrated by examples of typical design problem solutions. The

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1. Acoustics
2. Jet Engine Noise
3. Damping
4. Ground support equipment

I. AFSC Project 7231 Task 723104
II. Biomedical Laboratory
III. Contract AF 33(616)-5789
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